M. H. Ali

Fundamentals of Irrigation and On-farm Water Management

Volume 1

Springer

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ISBN 978-1-4419-6334-5 e-ISBN 978-1-4419-6335-2
DOI 10.1007/978-1-4419-6335-2
Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2010934381

Cover design: ©Pefkos-Fotolia.com

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Foreword

Agriculture is one of the few industries that has been creating resources continuously from nature. Sustainability of this industry is a crucial issue at now-a-days. Agricultural technologies are important to feed the growing world population. Agricultural engineering has been applying scientific principles for the optimal use of natural resources in agricultural production for the benefit of humankind. The role of agricultural engineering is increasing in the coming days at the forthcoming challenges of producing more food with less water coupled with climate uncertainty.

I am happy to know that a book entitled "*Fundamentals of Irrigation and On-farm Water Management*", written by Engr. Dr. M. H. Ali, is going to be published by Springer. The book is designed to cover the major fields of agricultural and environmental engineering such as weather, plant, soil, water, and basics of on-farm water management. The book will be quite useful for the students of agricultural engineering. Students of other related branches of engineering sciences, and engineers working in the field and at research institutes will also be benifited. The book may serve as a text book for the students and as a practical hand-book for the practitioners and researchers in the field of irrigation and on-farm water management. Utilization of the recent literature in the area and citation of relevant journals / reports have added a special value to this book. Considering the topics covered, engineers, scientists, practitioners, and educators will find this book as a valuable resource.

I hope this text-book will be used worldwide to promote agricultural production and conservation of the most important natural resource, water.

Mymensingh, Bangladesh
23 March, 2010

Dr. M. A. Salam
Director (Research)
Bangladesh Institute of Nuclear Agriculture

Preface

Water is the scarcest resource. Importance of judicious use of water in agricultural sector for sustaining agricultural growth and to retard environmental degradation needs no elaboration. Judicious use of water for crop production requires knowledge of weather, soil, crop, water quality, and drainage situation. Increasing efficiency in conveyance and pumping systems also are of great concerns. Irrigation management strategy practiced in normal soils may not appropriate in problematic soils such as saline soils and drought prone areas. It is also utmost important to pay attention to the economics in production system and all aspects of supply & demand management of water. This book covers all of the above aspects. In addition, the book covers some recent dimensions such as pollution from agricultural fields, modeling in irrigation & water management, and application of geographical information system (GIS) in irrigation & water management.

Sufficient workout problems are provided to explain the application of theory/methodology in practice. Data sheets (with sample data) are provided for different methods to understand the procedure easily.

This comprehensive and compact presentation of the book will serve as a text book for undergraduate students in Agricultural Engineering, Biological Systems Engineering, Bio-Science Engineering, Water Resource Engineering, and, Civil & Environmental Engineering. It will also be helpful for the students of relevant fields such as Agronomy, Biological Sciences, Meteorology, Ecology and Hydrology. Although the target audience of the book is undergraduate students, post-graduate students will also be benefited from the book. It will also serve as a reference manual for field engineers, researchers and extension workers working in the above mentioned fields.

It was tried to keep the language simple as possible to make understandable to all category of readers having different language origins. Throughout the book, the emphasis has been given on general description and principle of each topic, and tried to cover experimental and technical details. However, the comprehensive journal references in each area (at the end of each chapter) should enable the reader to pursue further study of special interest. In fact, the book covers broad interdisciplinary subjects. The subject matter has been splitted into

25 chapters in two volumes to clearly specify different topics so as to make more understandable to the readers. This volume (volume 1) covers fundamental aspects, and the second volume covers application aspects of irrigation and water management.

Mymensingh, Bangladesh Dr. M.H. Ali

Acknowledgements

I acknowledge the co-operation, suggestions and encouragement of the faculty members of the Department of Irrigation & Water Management, Bangladesh Agricultural University. I would like to thank Engr. Dr. M.A. Ghani, former Director General of Bangladesh Agricultural Research Institute, and World Bank Country Representative, Bangladesh, who critically reviewed the content and structure of several chapters of the Book.

I am grateful to the authority of Soil Moisture Co., CPN Co., and Raj Instrumentations for supplying the pictures of their products and giving permission to use the same in the book. I am also grateful to the authority of FAO and IRRI for giving permission to reproduce their some material.

I am thankful to Dr. M.A. Salam, Director (Research), Bangladesh Institute of Nuclear Agriculture, for going through the book and writing a few words about the same in the form of 'Foreword'.

My sincere thanks are also due to my affectionate wife Anjumanara Begham, daughter Sanjida Afiate and son Irfan Sajid, for their support, understanding and patience during preparation of the manuscript.

Contents

Chapter 1
Introduction: Perspectives and General Concept of Irrigation

Humans cannot produce their own food, but depend on the plant community for their food and fiber, directly and indirectly. Plants can produce their own food by using the natural resources such as soil, water, air, and sunlight. They can also produce more than they need for their survival and reproduction. Plants can not survive and produce their food without water. One of the main factors for the intensification of the agricultural production of plants is irrigation (artificial application of water to the plants' root zone). To get the optimal benefits from irrigation, it is necessary to calculate the required quantity of water in dependence of some parameters, for example, of the environment, the subsurface geo-hydrological condition, the type of crop, and the stage of its growth.

Irrigation of different modes and types has been practiced since ancient time. But with the rapid increase in population and industrialization, the demands on available water resources have increased in both the quantity of water required and the quality standard. Increased demands currently being placed on water supply have necessitated broader concepts in the application of engineering principles than those originally envisioned. In recent times, some of the fundamental aspects are: ways to obtain knowledge of specific processes within a complex system of interacting and interdependent phenomena, and then to reintegrate such knowledge so as to obtain a comprehensive and accurate solution of the phenomena.

1.1 Availability of Water in the Earth

Water covers about 70% of the earth's surface, but it is difficult to comprehend the total amount of water when we only see a small portion of it. The oceans contain about 97.5% of the earth's water; land, 2.4%; and the atmosphere, less than 0.001%. We get water from the sources of surface water, groundwater, and rainwater. Surface sources include natural depressions, lakes, ponds, rivers, reservoirs, etc. The volume of fresh water on the earth is about 0.25% of the earth's total water. About 0.3% of the fresh water is held in surface storage, while the remainder is

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DOI 10.1007/978-1-4419-6335-2_1, © Springer Science+Business Media, LLC 2010

stored as glaciers, snow, and underground aquifers. Of all the fresh water on earth, groundwater holds about 30%.

1.2 Variability of Water with Time and Space

The existence and quantity of water on the earth's surface vary with time and space. The global water cycle encompasses the distribution and movement of water in its three phases (solid, liquid, vapour) throughout the earth system. These include precipitation, surface storage, groundwater, surface and subsurface runoff, oceans, cloud, atmospheric water vapour, soil moisture, etc. The yearly precipitation amount varies greatly from place to place (spatial variability), and its distribution throughout the year (temporal variability) is also highly erratic and variable. The spatial and temporal variability of water on the earth makes water a critical resource.

1.3 General Concept of Irrigation

Plants need water for proper growth and development. The crop's demand for water must be met by the water in the soil, via the root system. Application of water to meet the crop water demand at the proper time in the proper way is termed irrigation. If the crop water demand is met by other ways (such as rainfall, capillary rise from groundwater table, etc.), there is no need of irrigation. Irrigation requirement for cereals and noncereals are not the same. Among cereals, irrigation requirement of rice is the highest. On the other hand, irrigation requirement of wheat is less when compared with that of rice. Proper irrigation scheduling also affects the irrigation requirement of different crops.

1.3.1 Irrigation Scheduling

The problems that are involved in irrigation scheduling are as follows: (1) when to irrigate, (2) how much to irrigate, and (3) how to apply irrigation water? The amount of irrigation is obtained through field measurement or predicted through indirect methods. The amount of irrigation is defined as the depth of water needed to meet the crop water loss through evapotranspiration under the growing environment. Although both timing and amount of water applied affect irrigation water productivity, timing has the greatest effect on crop yield and quality because at some growth stages, excessive soil moisture stress caused by delayed irrigation can irreversibly reduce the potential yield or quality or both. Different approaches used for irrigation scheduling are soil moisture basis, pan evaporation, leaf water potential, and growth stage basis. In all these approaches, the water demand can be met by full or partial irrigation.

1.3.2 Full Irrigation

Under adequate water supply (i.e., full irrigation), the crop water requirement is fully met. Crop water consumption ($\mathrm{ET_a}$) in this case is equal to the maximum evapotranspiration ($\mathrm{ET_m}$), i.e., $\mathrm{ET_a} = \mathrm{ET_m}$. No water stress develops under such conditions, and crop yield (Y_a) is expected to be potential yield (Y_m), i.e. $Y_\mathrm{a} = Y_\mathrm{m}$ (if other production factors are not limiting).

1.3.3 Deficit Irrigation

Under limited water supply (i.e., water stress or water deficit), the level of soil water status within the plant root zone is less than what would be under full irrigation. Crop water consumption in this case (ET_a) falls below maximum evapotranspiration (ET_m), i.e. $ET_\mathrm{a} < ET_\mathrm{m}$. Under such conditions, water stress will develop in the plant, which will adversely affect crop growth, and therefore the expected yield (i.e., actual yield, Y_a) will be less than the potential yield, i.e. $Y_\mathrm{a} < Y_\mathrm{m}$.

1.4 Global Outlook: World Population and World Water Use

The earth's population is projected to be about 10 billion by the year 2050 (U. N. Population Fund 1993). To keep pace with a galloping population growth, we are forced to produce more and more food. This force boosts agriculture, which ends up boosting pollution inputs into the water cycle.

1.4.1 Trend of World Water Use

Agriculture uses up more than 60% of available water supplies and, as such, it is the single largest consumer of water (Fig. 1.1). To a great extent, agriculture threatens global water resources in terms of both quantity and quality. The needs for improving water-use efficiency (WUE) in crop production and sustainable use of water resources are clearly urgent. In irrigated areas, improvement of water management on farms is the first step toward the conservation of a diminishing natural resource, and it is therefore important to find production systems able to use water more efficiently.

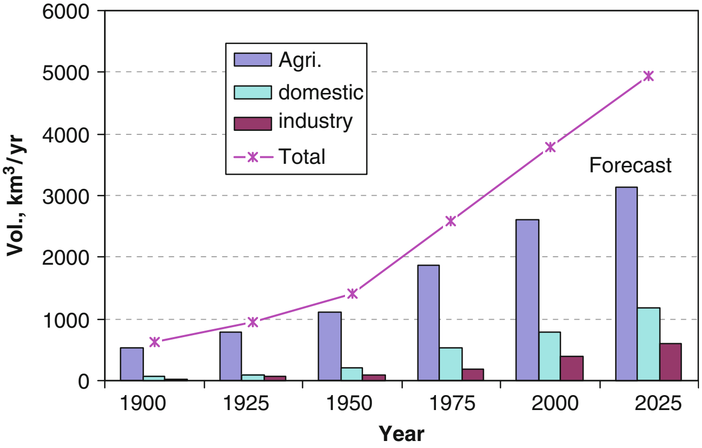

Fig. 1.1 World water use by sector [adapted from UNEP (2008)]

1.5 Challenges and Opportunities in Irrigation and Water Management

1.5.1 Challenging Factors

Challenges in irrigation and water management for world food security and agricultural trade arise from several aspects:

- Domestic resources condition
- Restriction of economic development level
- Climate change
- Pollution of water resources due to industrial and agricultural effluents
- Competition of water among different sectors of users
- International markets and price

Because of unequal distribution of world natural water resources, the water management and agricultural development level of different countries are very unequal. Many developing countries are confronted with shortages in per capita resources because of their large populations. Domestic food production can not meet the consumption demand. Uncertainty of future natural rainfall due to global warming and climate change faces the water management issues in more uncertain.

1.5.2 Opportunities

For better water resources management toward better world agricultural development and food security, important measures such as enhancing water management technology development and utilization of new technologies in all aspects of agriculture should be adopted. Specially, more crops per drop of water (i.e., water productivity) may be achieved through improved irrigation methods and means. Faced with a continuous large gap between globally potential and attainable water productivity, adoption of multiple options would play a promising role in enhancing water productivity and satisfying regional food requirement for the current as well as the future centuries. Globally, water resources may be used more efficiently when food is imported from the countries with high crop water productivity (CWP) to the countries with low CWP.

1.6 Physiographic and Economic Factors Affecting Irrigation and Water Management: Case Study, Bangladesh

Bangladesh lies between 20° 34′ and 26° 38′ North latitude and 88° 01′ and 92° 41′ East longitude, covering an area of 14.839 million hectares (ha). Bangladesh has a land frontier of 4,398 Km and a coastline of 740 Km. It is bordered on the west, north, and east by India; in the south-east by Myanmar (Burma); and in the South by the Bay of Bengal. The mountains of India greatly influence the hydrology of rivers that flow from them. The great Himalayan range of the north has a major role in influencing the climate of the country.

1.6.1 National Economy and Agriculture

The economy of Bangladesh is primarily dependent on agriculture. Agriculture is acknowledged as the principal source of income and livelihood for the vast majority of the population (~84%), either directly or indirectly. The agricultural sector registers as the second largest contributor to Gross Domestic Product (GDP): its share was 15.35% in the Fiscal Year 2006–2007 (BBS 2008). About 57% of the labor forces are employed in the crop sector. Performance of this sector has an overwhelming impact on poverty alleviation, food security, employment generation, human resource development, etc.

1.6.2 Basic Physical Factors in Agricultural Production

The development of agricultural production in Bangladesh is dependent on three basic physical factors: soil, land type, and water. Bangladesh, like most countries, has several soil types. The land is predominantly flat and prone to flooding. The existing land-man ratio (0.058 ha/person, cultivable land) [adapted from BBS

(2007)] is very unfavorable, and apart from some coastal and hilly areas, which present special difficulties, almost all available land is under cultivation. Rainwater, irrigation, and the residual soil moisture are essential for growing crops. The use of water in agriculture can be divided into two categories: the surface water use and the groundwater use. The aquifer is a natural underground reservoir (source of groundwater), where water is stored/recharged during the monsoon season. Most aquifers of the country are semiconfined. The groundwater is withdrawn through pumping for use during the dry season.

Because of its physiographic position (ocean in the south and orographic barrier, the Himalayas, in the north), monsoon rainfall occurs during the summer months (from April to August), and the winter periods (from November to February) are dry.

1.6.3 Challenges and Limiting Factors in Agriculture in Bangladesh

According to sources in the Agriculture Ministry, arable land is declining per year at the rate of about 1%. Land use intensity has already reached about 200%, perhaps the highest in the world. The land-man ratio will decline more rapidly over the coming years.

It is true that Bangladesh was once endowed with abundant fresh water resources, but this reserve is declining with time. Moreover, a vast area in the coastal zone comes into contact with saline water. The prospect of a greenhouse-induced climate change introduces additional uncertainty about the future availability of water, and a warmer climate would add to demands on the resources (Frederick 1997; Ali and Adham 2007).

Fresh water resources are finite, and most of the economically viable development of the resources has already been implemented. Establishment of additional surface water resources will lead to numerous environmental costs. Hence, in the future, greater reliance has to be placed on water saving measures and improved operational skills for tackling a water limited situation.

At this point of time, agriculture confronts a pressing demand on yield growth with declining land area. Fresh water scarcity, soil degradation, imbalance of fertilizer application, and knowledge gap of marginal farmers have led the agricultural sector to face a great challenge. There is no choice but to boost up the production. If we have to achieve the targeted production, it has to be achieved with less land, less water, and without causing damage to the environment.

1.6.4 Physical Features of Bangladesh Influencing Water Resources Utilization

Utilization of water resources by any country is profoundly affected by its physical features, and origin and distribution of water resources. Its topographical condition makes Bangladesh a drainage basin, with more than 90% of waters draining outside Bangladesh. There are 310 rivers in Bangladesh, of which 54 come from India. Through a complex river system, Bangladesh drains an area of about 1.72 million km^2 of the catchment areas of the Ganges, the Brahmaputra, and the Meghna, of which 7% lies in Bangladesh. The excess water during the monsoon causes wide spread flooding, which damages crops. The inadequate flow in the river system during the dry months hampers irrigation, obstructs navigation, aggravates intrusion of salinity to inland areas, and seriously affects the flora and fauna. The water problem in Bangladesh was exacerbated when India started withdrawal of water from the rivers Ganges, Teesta, and 40 other common rivers.

Generally, the groundwater system is hydraulically connected with the river system. When a stream channel is in direct contact with an unconfined aquifer, the stream may recharge the groundwater or receive discharge (base-flow) from the groundwater depending on the relative water level gradient. Therefore, during dry periods, the observed stream-flows in the rivers are mostly contributed by the aquifer storage as base-flow. Groundwater abstraction using tube wells, particularly shallow tube wells (STW), near the river is directly at the expense of river flow.

1.6.5 Climate and Cropping Pattern

Bangladesh is located in subtropical Asia, which has a subhumid and subtropic climate. Monsoon rainfall during summer influences agriculture and cropping pattern. The total amount of annual rainfall for the country is high. The mean varies from 1,200 to 5,800 mm, but its distribution is highly erratic, both in terms of time and space (Fig. 1.2). About 70–80% of the yearly rainfall occurs during the months from June to September, leaving the most productive dry season (November–March) with extremely inadequate rainfall for crop growth. As a result, a substantial proportion of the annual rainfall is lost as runoff and evaporation. The months of April and May, and sometimes September, frequently experience long dry spells or insufficient rainfall for crop growth. In addition to this, the spatial variability of rainfall is particularly high. During the non-rainy months, the river flows dwindle to a fraction of their flood flows and some streams dry up altogether. Daily maximum and minimum temperature patterns are shown in Fig. 1.3.

The climate of Bangladesh is suitable for the growth and cultivation of a wide variety of tropical and subtropical species. The cropping pattern depends on a number of factors such as climate (rainfall, temperature, light), topography, soil type, etc. The crops in this country are grown throughout the year in three distinct cropping seasons. The first is the “Kharif-I” season lasting from the end of March to May, which is a moderately humid period. The second is Kharif-II season or the hot monsoon season, covering the period from May to September, is characterized by high humidity and low solar radiation. More than 80% of the total annual rainfall occurs in this period. Finally, we have the “Rabi” season from mid-October to early March, which is a cool, dry winter season.

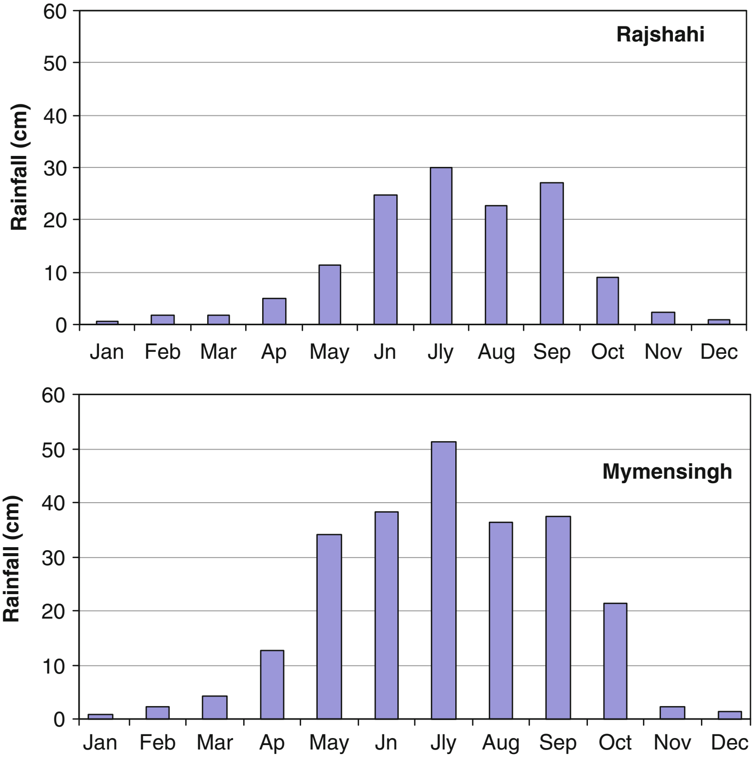

Fig. 1.2 Rainfall distribution throughout the year at two locations of Bangladesh

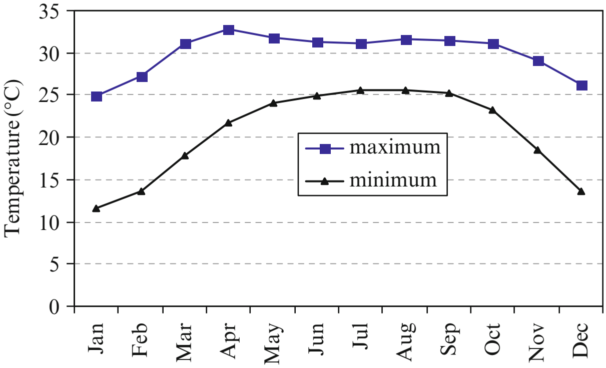

Fig. 1.3 Daily maximum and minimum temperature pattern throughout the months of the year

The Kharif crops include rice, jute, sugarcane, sesame, mugbean, etc. Rabi crops include boro rice, wheat, potato, mustard, pulses, vegetables, spices, etc. Hossain (1990) documented 60 variations in cropping patterns, which depend on the local agro-climatic conditions. Most of the cropping patterns are based on rice or have rice in common with other crops.

Water dependency of the crop seasons are as follows:

Kharif- I: Partially irrigation dependent

Kharif II: Natural rainfall dependent

Rabi: Irrigation dependent

"Aus" and "transplanted aman" rice/paddy are the main cereals in Kharif I and Kharif II, and wheat and boro are the main cereals in the Rabi season. Rice is the major food crop of Bangladesh. It covers about 76% of the total cropped area both in summer and winter seasons.

1.6.6 Major Source of Irrigation Water in Bangladesh and Concern of Sustainability

The major source of irrigation in Bangladesh is groundwater (covers about 76.5% of the total irrigated area) (BBS 2007). Groundwater is abstracted through deep tube wells (DTW) and shallow tubewells (STW). The groundwater is mainly used for Boro rice cultivation during January–May. Under irrigated conditions, Boro rice is regarded as a highly water consuming crop.

With the advent of technology (machine power), man's capacity for groundwater extraction has increased manifold. At present, the aquifers, from which the groundwater is extracted, are not in dynamic equilibrium in most parts of the country. As a general practice in Bangladesh, where groundwater is the main water resource, pumping greatly exceeds recharge resulting in lowering of the groundwater levels at alarming rates. Groundwater in Bangladesh is available at comparatively shallow depths during the period of August–October (at the end of the rainy season) and is lowest in the period of April–May (at the end of the dry season). There are several areas of Bangladesh (e.g., Rajshahi, Bogra, Pabna, Mymensingh, and Dhaka), where groundwater abstraction is causing a large decline in groundwater levels during the periods of dry season. Because of the declining groundwater level, most of the shallow and hand tube wells (which have been installed for supplying irrigation water and drinking water) have been a failure. The reason is that the pumping level has already gone beyond the maximum practical suction limit of centrifugal pumps installed for running STWs. Therefore, there are obvious limitations to the extent of groundwater-use. Deep drilling may only help to mine the water accumulated over centuries. Such mining efforts may not provide a long-term sustainable support for development.

1.6.7 Considerations in Current Water-Starved Situations

Because of the declining trend of the water table and the increased costs of irrigation, there is a need to evaluate strategies for crop production with respect to crop rotation or cropping pattern and water management. In the above (prevailing) circumstances, for maximizing the economic returns from the limited water resources available, it is more advantageous to encourage the low water consuming crops such as wheat, maize, oilseeds, pulses, and vegetables. It can be seen that the net water savings in growing wheat run up to about 50–80% when compared with that of growing rice. Agricultural production and livelihoods in dry areas can be sustained only if priority is given to improve water productivity and enhancing the efficiency of water usage. In other words, more food, feed, and fiber must be produced using less water.

Questions

1. Narrate the distribution pattern of water on the earth.
2. Discuss the variability of water on the earth in the temporal and spatial scales.
3. Briefly describe the background and concept of irrigation.
4. Sketch the water-use trend by sectors in the global scale.
5. What are the opportunities and challenging factors in irrigation and water management?
6. Discuss the physiographic and economic factors affecting irrigation and water management in your area.

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Chapter 2
Fundamentals of Irrigation Development and Planning

Irrigation has historically been a major factor for increasing crop productivity. Irrigation raises the productivity of land directly by providing sufficient water supply to raise the yield per hectare per crop and by allowing a second crop to be grown during the dry season when yields are potentially higher. But the development of irrigation facility in itself (consequently the productivity and profitability) depends on several factors, which should be understood clearly and which are essential for the successful operation of an irrigation system. This chapter deals with these factors and synthesizes each factor. In addition, irrigation development in Asia and the Pacific region, the impact of irrigation on the environment and ecosystem, and the land classification system for irrigation are discussed.

2.1 Factors Affecting Farm Production

The upper limit of crop production is set by the genetic potential of the crop and the climatic conditions, provided water and nutrient availability are not limiting factors. Irrigation has historically been a major factor for increasing crop productivity. Irrigation raises the productivity of land directly by providing sufficient water supply to raise the yield per hectare per crop and by allowing a second crop to be grown during the dry season when yields are potentially higher. It also increases yields indirectly by raising the profitability of modern crop varieties with fertilizer use. But such increase in productivity or profitability depends on numerous other factors. The factors affecting farm productivity are described below.

2.1.1 Agro-Ecological Factor/Constraint

Climatic variability involving yearly variation in the onset and withdrawal of the rainy season, hailstorms, incidence of heavy rainfall, high humidity, cold or heat stress, cyclones and associated storm surges in the coastal areas.

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DOI 10.1007/978-1-4419-6335-2_2,

2.1.2 Soil Factor

Deterioration of soil health due to continuous cropping, decline in productivity, steep slopes, shallow soils and soils poorly suited for terracing in hill areas, imbalanced/under-fertilized soils.

2.1.3 Hydrological Factor

Restricted opportunities for cultivation of rain-fed rice, seasonal droughts and floods, flash floods, impeded drainage/water-logged soils.

2.1.4 Crop Factor

Yield potentiality, crop duration, quality of seed, efficiency of nutrient/fertilizer use.

2.1.5 Water Management

Inefficient on-farm water management and inadequate drainage.

2.1.6 Fertility Management

Imbalance in the use of major and minor nutrients, absence of measures to correct the prevailing micro-nutrient deficiencies, nonintroduction of cropping system-based fertilizer use and management.

2.1.7 Socio-Economic Factor/Constraint

Lack of farmers' access to production technology, lack of specialized physical and human factors, inadequate agricultural credit, unavailability of inputs at the proper time, market limitations (output side), adoption of risk aversion strategy, development and use of cost-effective and environment-friendly production technologies.

2.1.8 Other Management Factors

Nonpreparedness to meet the problems arising from environmental hazards; nonpreparedness to develop contingency plans and crop life-saving techniques; neglect in correcting the problems of soil such as salinity, sodicity, acidity, organic matter, etc.; nonarrangement for providing crop life-saving irrigation; nonadoption of proper control measures for insects and pests; nonestablishment of minimum desired level of plant population; and unconcern for timely agricultural operations.

2.2 Important Factors Affecting Irrigation Planning and Development

The major factors influencing development of irrigation facility are as follows:

- Soil
- Climate
- Topography
- Water source
- Crop(s) to be cultivated
- Energy
- Labor
- Capital
- Commodity/product market
- National policy and priority
- Institutional infrastructure
- Economic factor
- Environmental aspect
- Socio-cultural aspect

2.2.1 Soil

Suitability of a land for irrigated agriculture depends on soil characteristics, soil profile, geological deposits, and surface texture. Certain soil conditions are needed for profitable, diversified crop production under sustained irrigation. These include the following:

- Adequate moisture holding capacity for the proposed irrigation and cropping pattern
- Adequate infiltration rate to facilitate replenishment of soil-water lost through evapotranspiration, to minimize erosion, to prevent excessive deep percolation under the proposed method

- Adequate internal drainage through the root zone for proper aeration, replenishment of soil-water reservoir, and leaching of salts
- Sufficient depth of suitable soil profile to allow necessary development and provide adequate storage of moisture and plant nutrients
- Suitable texture, structure, and consistency to permit necessary field operations in time
- Absence of hazardous amount of acidity, sodicity, salinity, or any other toxic elements

2.2.2 Climate

Crops have their optimum climatic requirements for normal growth and development, and fruiting. Beyond the desired limit, crops cannot grow properly and produce flower. Some of the important climatic elements are maximum temperature, minimum temperature, night temperature, and day length. Atmospheric water demand or crop evapotranspiration should also be taken into account for irrigation planning.

2.2.3 Topography

Topography, vegetation, biological activity, and time give a soil its characteristics or soil profile. Suitability of a land for irrigated agriculture depends largely on its topography as it determines the choice of irrigation method. It can also affect labor requirement, irrigation efficiency, drainage, erosion, size and shape of fields, range of possible crops, and land development. Operational expenses increase with the surface feature, field size, stoniness or bush/tree cover, and surface drainage requirement.

2.2.4 Water Source

In planning and developing an irrigation project, source(s) of water should be identified so as to ensure continuous water supply. In water resource development, harmonization of the different demands for water, establishment of irrigation priority rights between upstream and downstream users, and consideration of the rights of the existing users of water from flood, which may be modified by dams, is essential. It requires a formal institutional approach based on local experience. If the project is based on groundwater resource, sustainability of the resource should be considered.

2.2.5 Crop(s) to be Cultivated

Depending on the crop type, the water requirement varies. Hence, water resources should be planned on the basis of the major crop(s) and cropping pattern. The factors influencing the choice of crop are the local/national demand (to ensure self sufficiency or to discourage import), profitability factor (to export, in response to foreign demand), ease of marketing and market demand, etc. The materialization of the planned cropping pattern is a must for protecting the soil (against salinity, alkalinity, aridity, etc.) and for feeding sufficient water to irrigation network areas.

2.2.6 Energy

If water is to be pumped from the source to the irrigated area/field, then the energy source for the pumping is a major consideration. If an electric transmission line is to be constructed, it will require an investment. If the pump is to operate with a diesel engine, it will certainly create an environmental problem.

2.2.7 Labor

For the implementation of irrigation projects, a huge amount of human labor will be required depending on whether the project will be human labor based, or a mechanized one. This point should be taken into account while planning for an irrigation project.

2.2.8 Capital

Establishment of a large scale irrigation facility requires large capital investment. Expenditure for irrigation consists of capital investments and recurrent expenditures for operation and maintenance. It should be checked whether the money is available from the local/central government, a public agency, or from a foreign donor. After ensuring that money is available, the project should be started.

2.2.9 Commodity/Product Market

An appropriate marketing system or facility of marketing the products to be produced from the irrigation project area should be considered for an economically sustainable production system. The producers are obliged to cultivate crops with relatively high profitability and market guarantees. Lack of viable product markets and marketing institutions are major problems for sustaining production and effective irrigation development. Government organizations and other institutions should be developed to overcome marketing problems. The slow growth of markets for high-value crops sharply reduces the projected profitable crop mix that would warrant the frequently high costs of irrigation investments.

2.2.10 Economic Factor

A major problem affecting irrigation development projects is the high cost of construction yielding low benefits from agriculture. To achieve efficiency, irrigation investments must be fully recoverable, that is, the present value of public revenues to be generated from the project must be at least equal to the present value of cost. Who should pay for the cost (and in what proportion) depends on the distribution of benefits from irrigation. The beneficiary farmers must pay the cost in proportion to the benefits they receive.

Several factors affect the benefits from an irrigation project: low price of the crops, the prevailing low yields, and the high input costs are examples. All these factors are linked to the management level, and may vary from location to location, and region to region. Truly functioning credit systems for small-scale farmers or effective agricultural extension services may influence the prevailing situations.

2.2.11 Environmental Aspect

On the one hand, diversion of existing river-flow in the dry zone may affect downstream users in terms of quantity or quality or both. On the other hand, wet zone rivers may have large unutilized water resources flowing through heavily populated areas. In such a case, any large scale water resource development in these areas would involve displacement of people and property, which is socially and politically undesirable. These points should be taken into consideration and the regional or national benefits should be optimized.

Other environmental issues such as drainage effluents, siltation and sedimentation, water logging, development of salinity and acidity in soils, emission of methane gas from agricultural fields, distortion of natural habitat and bio-diversity, etc. should be considered while planning an irrigation project.

2.2.12 National Policy and Priority

Irrigation development or implementation of irrigation projects largely depends on the national/governmental policy and priority issues. The government may promote irrigation development to increase and stabilize food production in the region. Despite a proposed irrigation development project being not economical (in terms of estimated net return and cost, and economic rates of return), the government can establish such a project considering regional/national food security, local employment opportunity, opportunity of establishment of local industry, and long-term savings in foreign currency.

2.2.13 Socio-Cultural Aspects

The implementation of irrigation projects will bring changes in land use pattern and intensity, land and labor productivity, household resource requirements, and tenure issues, which require management and institutional consideration. These socio-economic and institutional factors affect irrigation development.

2.2.14 Institutional Infrastructure

New construction or rehabilitation of existing irrigation systems requires operation and maintenance, and financing and cost recovery. An institutional framework and infrastructure is necessary for analyzing policy decisions with respect to project section, design and construction, operation and maintenance, cost recovery, and administration.

2.3 Irrigation Development in Asia and Pacific Region

The Asia-Pacific region comprises 54 countries. Because of the vastness and diversity in terms of geography, topography, climate, ecology, and other natural conditions, as well as differences in socio-cultural, economic, and political systems, the region is grouped into five subregions: Central Asia, Northeast Asia, South Asia, Southeast Asia, and South Pacific.

The Asian and Pacific region extends over a total area of about 27% of the world's land area. With a concentration of nearly 60% of the world's population and over 60% of the world's irrigated land, the region is more densely populated and more intensively cultivated than any other region. Asia-Pacific is known for its highest potential renewable water resources in the world. But because of the large population, the region has the lowest water availability per capita.

2.3.1 Progressive Irrigation Development in Bangladesh

Up to the 1950s, Bangladesh (formerly East Pakistan, and even earlier, part of greater India) was dependent on traditional means of irrigation only, such as swing baskets, doans, etc. Modern tube-well irrigation technology was first introduced here in the early 1960s.

The dependence of Bangladesh's agriculture on the south-west monsoon and its consequent vulnerability have been recognized from the earliest times. In Bangladesh, the strategy for economic development during the early 1950s was focused on large-scale public projects undertaken to stabilize water regimes associated with rainy season rice irrigations. Investments then took two main forms: improvement of flood control and drainage, and development of supplemental irrigation during the monsoon season. This approach was institutionalized in 1959 with the creation of the East Pakistan Water and Power Development Authority (now Bangladesh Water Development Board, BWDB) and the development of the nation's first Water Resources Master Plan in 1964 (Satter 1999). Although the major emphasis was on flood control projects, small scale surface irrigation systems were tried out during the1960s. About 4,000 low lift pumps (LLP) were installed by the East Pakistan Agricultural Development Corporation (now "Bangladesh Agricultural Development Corporation," BADC) by 1967 (EPADC 1968). Programs to tap the subsurface water commenced in 1961 with the installation of about 400 deep tube-wells. Under the guidance of World Bank, an action plan focusing on food production, not flood protection, through small and quick yielding irrigation schemes was undertaken in 1972 (IBRD 1972). The new plan suggested a modest increase in large gravity projects, rapid growth in tube-well development, and constrained development of LLPs is limited. The expansion of LLPs was limited by the supply of dry-season surface water. Several large and small-scale development projects related to flood control, drainage, and

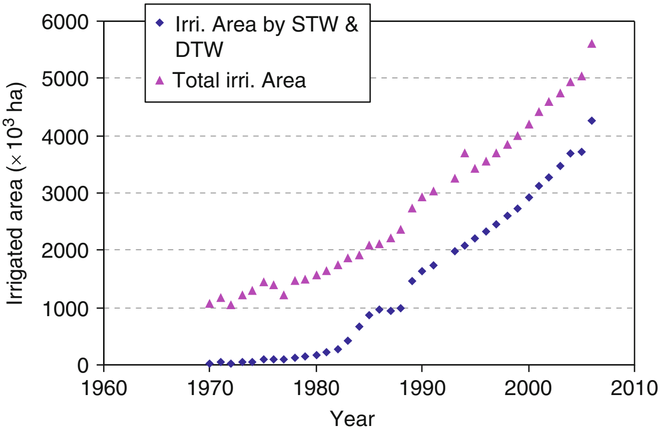

Fig. 2.1 Progressive expansion of irrigated area in Bangladesh

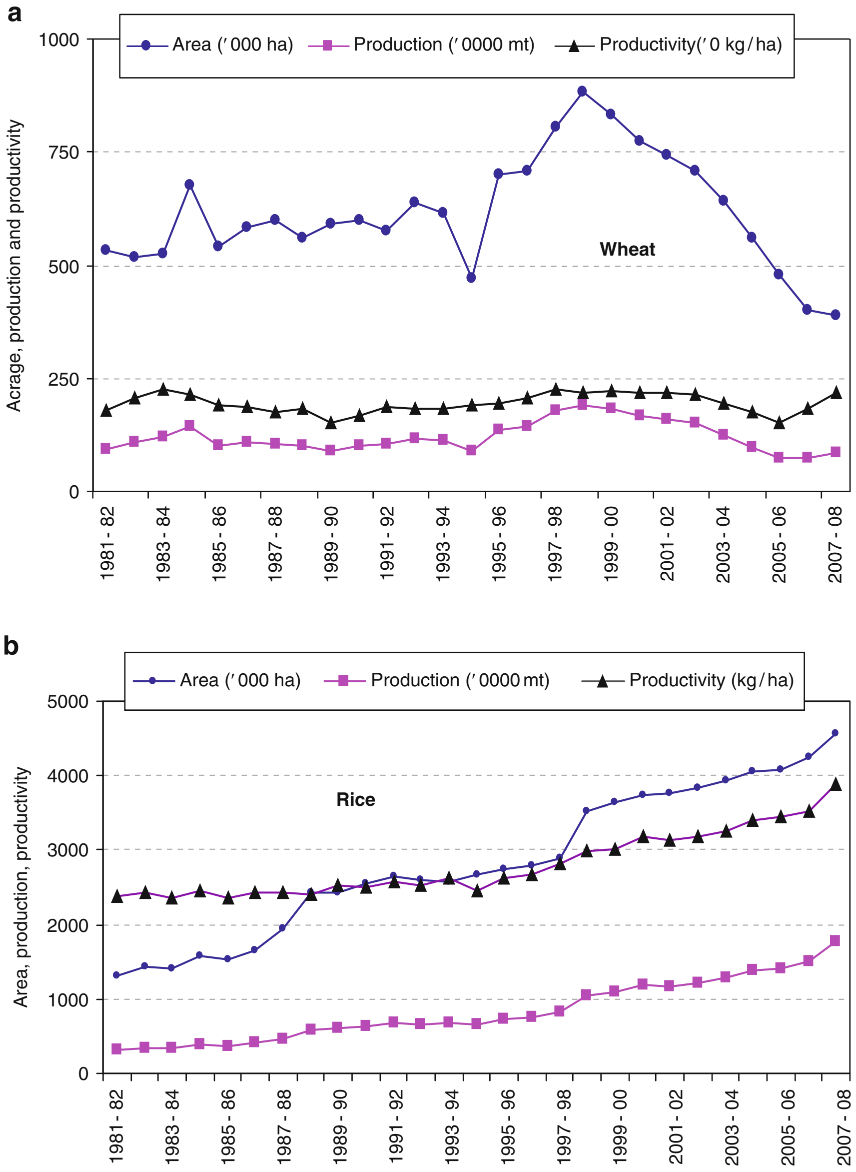

Fig. 2.2 Historic progress in acreage, yield, and productivity of (**a**) wheat, and (**b**) rice in Bangladesh

irrigation were implemented by BWDD. The government's main strategy for economic development during the second and third five-year plans was to undertake short-gestation, low capital, and quick yielding projects. This lead to a massive expansion in the tube-well programs, and by 1985, 17,000 DTW and

156,000 STW were in operation. The number increased to 24,059 DTWs and 348,875 STWs by the end of 1992–1993 (BBS 2001). This massive as well as rapid expansion of the tube-well program has led to overdraft of groundwater in some areas of the country (especially in the north-western, Rajshahi region). The number increased to 27,117 DTWs and 1,128,991 STWs in 2005 (BADC 2005) and 32,174 DTWs and 1,374,548 STWs in 2008 (BADC 2008).

Progressive expansion of irrigated area is shown in Fig. 2.1. A rapid increase during 1985–1986 occurred due to the corresponding increase in pumps and tube-wells. The trend of historic progress in acreage, yield, and productivity of wheat and rice is shown in Fig. 2.2. The availability of water (through pumping) increased the rice area over the years. The productivity of rice increased with the planting of high yielding varieties, fertilizer use, and improved management practices. The wheat area fluctuated and decreased to some extent. This is mainly because rice is the principal staple food grain of the people of Bangladesh.

2.3.2 Irrigation Development in China

About half of China's territory is arid and semi-arid. In the north-western part of China, the annual rainfall is less than 250 mm and without irrigation there would be no agriculture. In the north-eastern and northern parts of China, the annual rainfall is 400–600 mm (Guangzhi et al. 2009), which substantially falls in summer and there is a spring drought almost every year. Irrigation is a necessary condition for agricultural development.

China has a long history of irrigation. About 2,000 years ago, their forefather had already built the world-famous Dujiangyan irrigation district in Sichuan Province. After several rehabilitation and modification many times, it is still being used. With an irrigation area of ten million mu (1 mu = 1/15 ha), it has become an economically developed region of the highest food production in Sichuan Province.

In 1949, the irrigated area of the whole country was 240 million mu accounting for only 16% of the country's farmland. Since 1949, China has engaged in a vigorous water conservancy program, including the construction of 864,000 reservoirs of various sizes and numerous pumping stations with total installed capacity of 53,700 MW as well as two million tube-wells (Puli 1985). The irrigated area increased from 16 million hectares in 1949 to 46 million ha in 1983. By the end of 1998, irrigated area had attained 800 million mu, accounting for 40% of the farmland (Guangzhi et al. 2009).

In 1949, the water use for irrigation was approximately 100 billion m^3. On the one hand, with the increase of irrigation area, the use of water for irrigation gradually rose and reached 358 billion m^3 in 1980. After that, irrigation water use has been stabilized. On the other hand, industrial and municipal water uses have increased rapidly, thus leading to the dropping of the proportion of irrigation use in the whole water use of the country (Fig. 2.3).

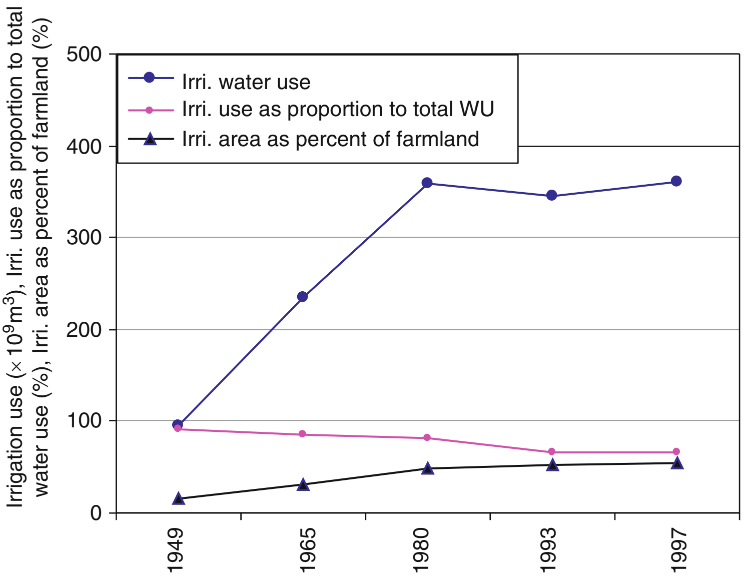

Fig. 2.3 Progressive irrigation water use, proportion of irrigation water out of total water use, and area irrigated as a percent of total farmland in China (adapted from Guangzhi et al. 2009)

2.3.3 Irrigation Development in Iran

Iran is located in the northern hemisphere between 25° and 40° longitude, and 43.5° and 64.5° latitude, having surface area of about 1.48 million Km^2. There are two mountain ranges, the Alborz and the Zagros, and to the south, down lands of Persian Gulf, Oman Sea, and Caspian Sea are found. Thus, Iran has a high differential elevation of about 5,000 m. About 73% of the land is arid and semiarid.

The development of water resources in Iran has always been hindered by serious problems. To begin with, the precipitation distribution within the country shows marked variations from one region to another. Precipitation mean varies from 50 mm in the central, southern, and eastern areas to 1,500 mm in northern and western parts. In 6% of the land, it is less than 50 mm, and in other parts it varies between 200 and 1,000 mm, only in 1% of the land it is more than 1,000 mm (Messdaghinia and Alavi 2010). The Caspian lowlands, representing 10% of the total area, has one-third of all the precipitation falling on Iran, while many parts of the central plateau receive scarcely any water at all.

Precipitation occurs over most of Iran between October and March, when temperature is low and agricultural activity is at a minimum. Fortunately, however, much of it in the upland regions falls as snow, and water is therefore stored in the solid form until snowmelt begins in the late spring and early summer. Rivers fed by melting snows have peak discharges during the months April, May, and June.

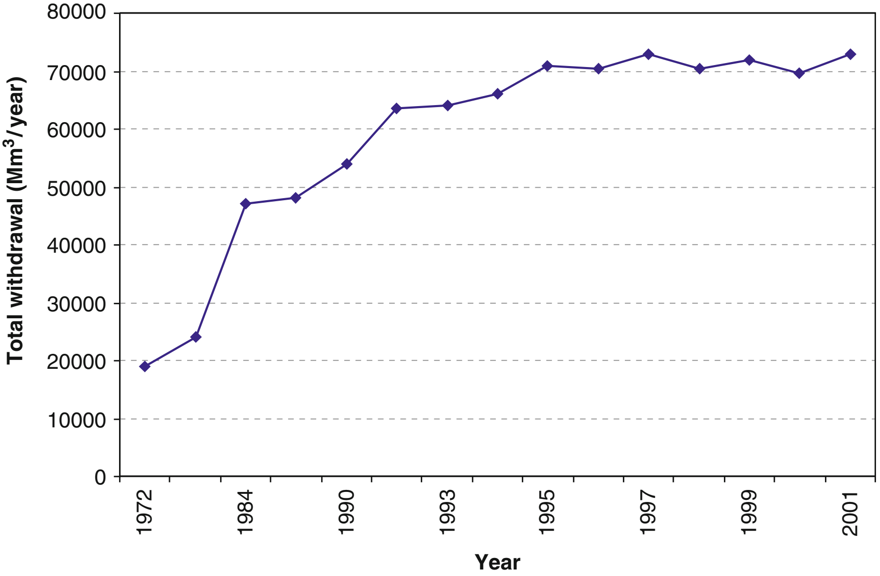

Fig. 2.4 Water withdrawal from groundwater resources in Iran during 1972–2001 (after Mesdaghinia and Alavi 2010)

In Iran, water is a critical component for agriculture, industrial, and urban development. Because of insufficient rainfall, conservation and water management in Iran was a matter of great concern. Now it is becoming increasingly more and more important. The total incoming water to Iran is estimated to be 415 × 10^9 m^3 of which 98% is from atmospheric precipitation (Mahmoud 1994). The total water exploited is 94 × 10^9 m^3 with the agricultural sector being the largest consumer of water. The storage capacity of the existing dam is about 25 × 10^9 m^3. Large increase in water demand with very little recharge have strained Iran's groundwater resources resulting in serious decline in groundwater level and quality (Madaeni and Ghanei 2004). Water withdrawal from groundwater resources during the period 1972–2001 is shown in Fig. 2.4. Withdrawal has an increasing trend.

2.4 Impact of Irrigation on Environment and Ecosystem

A fast growing population in the world requires a growth in agricultural output. Irrigation is often a condition for agricultural intensification in arid and semiarid regions. Current agricultural practices involve deliberately maintaining ecosystems in a highly simplified, disturbed, and nutrient-rich state. Intensification of agriculture to bridge the gap between food production and food needs in many countries have already transformed the environment and ecosystem. The recent intensification of agriculture, and the prospects of future intensification, will have major detrimental impacts on the nonagricultural and aquatic ecosystems of the world.

Impact of irrigation development on social and environmental aspects may be positive or negative.

2.4.1 *Positive Impacts*

2.4.1.1 Health

Irrigation water use affect health by bringing water into close contact with people. This proximity can have positive health benefits by:

- Ensuring household food security and improving nutrition
- Providing with a reliable source of water for drinking and hygiene

2.4.1.2 Socio-Economic

Irrigation is generally considered as an effective way of increasing agricultural production (more land under crops, more crops per ha per year, more crop production per ha per season). As production increases, per capita income increases; and thus the socio-economic condition and livelihood improve. Thus the access to irrigation or development of irrigation facility has a positive impact and profound role to play on poverty reduction. The overall growth and technical change in the agricultural sector has large implications on expanding the economic base and poverty alleviation process in a region. Consequently, inequity of income is reduced over time.

2.4.2 *Negative Impacts*

Water maintains a host of natural ecosystems. Withdrawal of water from upstream can reduce the flow at downstream needed to sustain natural ecosystem. The off-take and diversion structures often deprive downstream users of their water.

Negative impacts of irrigation may be through the following:

1. Water quality degradation
2. Groundwater abstraction
3. Water-logging and salinity
4. Health risk
5. Simplification and homogenization of the world's ecosystem

2.4.3 Degradation of Water Quality

Agricultural intensification is often associated with cultural practices, which, when uncontrolled, can boost up the deterioration of water resource quality, mainly surface and ground waters. The doubling of agricultural food production during 1965–1999 years was associated with a 6.87-fold increase in nitrogen fertilizer and 3.48-fold increase in phosphorous fertilizer (Tilman 1999). A poor management of irrigation and drainage techniques, coupled with an inappropriate use of inputs (e.g., fertilizer, pesticides, herbicide, etc.), is one of the major causes of surface and ground water pollution within and around the irrigation schemes. This polluted water is often a source of pollution of rivers and water-tables nearby. The consequences of water pollution from agricultural sources may be diverse and sometimes disastrous. The main consequences are as follows:

- Human health consequences
- Ecosystem consequences
- Economical consequences

2.4.3.1 Human Health Consequences

The polluted water is one of the major sources of diseases across the world. According to the World Health Organization (WHO), about 4 million children die every year due to diarrheal infections (FAO, Irrigation and Drainage Paper, No. 55). The high level of nitrate concentration (NO_3–N) in groundwater (originated from Urea fertilizer, applied in agricultural field), which is a main drinking water source, is at a major risk. The nitrate causes cyanosis syndromes and has carcinogenic impacts when present in the stomach.

2.4.3.2 Ecosystem Consequences

Surface water pollution, and especially that polluted due to high nitrate and phosphate, is a serious ecological risk. This pollution causes destruction of live resources, and nonequilibrium of physical and biological environment, and aquatic ecosystem through the eutrophication phenomena. Drainage flows from irrigated fields can disturb the ecological balance by carrying excess chemical nutrients and pollutants into the ecosystem.

2.4.3.3 Economic Consequences

On the one hand, use of poor quality or contaminated water for drinking and other uses, and agricultural pollution have impact on economical aspects of other activities such as industrial, tourism, fishery, etc. On the other hand, rectification of polluted water quality is expensive and requires long-term investments.

2.4.4 Groundwater Abstraction

Unplanned and excessive groundwater abstraction for irrigation can cause considerable damage to ecologies. Overdraft results in the decline of the initially shallow water-table, drying up the natural springs and ponds. Saline water intrusion from sea may occur in the coastal area.

2.4.5 Water-Logging and Salinity

Where shallow saline groundwater exists, irrigation may results in raise of shallow water-table, and thus salinity problem. In addition, seepage from canal may results in local water-logging problem. In the Indus Plains in Pakistan, water-logging and salinity is an acute problem.

2.4.6 Health Risk

Irrigation water can increase certain health risks by:

- Bringing people into contact with waterborne and water-washed diseases
- Providing a breeding ground for mosquitoes that carry malaria

2.4.7 Simplification and Homogenization of the World's Ecosystem

The characteristics of the green revolution during the middle of last century are – control of crops and their genetics, of soil fertility via chemical fertilization and irrigation, and of pests via chemical pesticides. They have caused four once-rare plants (barley, maize, rice, wheat) to become the dominant plants on earth as human became the dominant animal. These four annual grasses now occupy 67, 140, 151, and 230 million hectares each, respectively, worldwide (Tilman 1999). These monocultures have replaced natural ecosystems that once contained hundreds to even thousands of plant species, thousands of insect species, and many species of vertebrates. Thus, agriculture has caused a significant simplification and homogenization of the world's ecosystem.

2.5 Land Classification for Irrigation

2.5.1 Concept of Land Classification

Land classification means grouping of land categories (soil and topography) that have the same relative degree of limitations (or hazards) for irrigation use at its present state for the same groups. Simply speaking, land class indicates the general capability of land for irrigation use. Land within a land class is alike or nearly alike in its potential to be developed and its response to a similar level of management.

2.5.2 Importance of Land Classification

In the context of irrigation development, the aim of land classification (sometimes referred as land evaluation) is to mapping an area to explore how well the land is suited to irrigation development, that is, to determine which class or classes of land should be so developed. The classification provides the following:

1. An inventory of land characteristics
2. The extent and degree of suitability of land for irrigation
3. Indicates relative capability for sustained production under irrigation
4. Identifies potential problems that may occur with irrigation
5. Facilitates making recommendations for appropriate management under irrigation
6. Facilitates optimal land resource utilization
7. Indirectly provides an economic assessment, that is, justify the expenditure on irrigating land

Land classification is used for various purposes. They are useful as source of information about soils for many kinds of general or broad area planning, and planning large-scale irrigation development projects. Land classification provides the means of making logical choices between alternative forms of development. In some countries and/or provinces, land classification is a mandatory requirement for irrigation activities.

2.5.3 Standards of Land Classification

The standards are used for the classification of lands for the formation of a new area/district, or for the reclassification of lands in a region.

2.5.3.1 Basis and Methods

Classification criteria may include both soil site characteristics and other criteria established at the time of mapping. The standards outline the minimum requirements with which any land must comply to be classified as “irrigable”, so they can be supplied with water. The standard for land classification for irrigation should include several criteria/factors:

- Soil
  - Permanent factors
  - Changeable factors
- Topography
- Availability of water
- Climate
- Predicted response to irrigation

Soil factors such as parent material, texture, effective soil depth, water holding capacity, and drainability are considered as the permanent land features.

Changeable factors include fertility, drainage, groundwater, salt content (salinity level), soil pH, and erodibility. Soil structure may be modified by physical and chemical processes. Relocation and chemical changes in soluble salts may occur as a result of irrigation. Micro-relief and characteristics of the soil profile can be altered by land forming, stone and brush removal, drainage, subsidence, or by increased erosion due to irrigation.

The elevation of the land in relation to the water surface elevation in the laterals may be important in some cases. Topographic features include size and shape of fields, relief, stoniness, earth moving requirement, bush/tree cover, surface drainage requirement. These features are important because they determine the irrigation method. Topographic features also affect irrigation efficiency, labor requirement, cost of land development, drainage, erosion, etc. Soil and topography ratings may be determined separately and combined into a land class that reflects the suitability of land for irrigation farming.

There is no justification for irrigation development in areas where rainfall does permit crop production.

Land classification for irrigation also involves predicting how land will respond after development and the application of irrigation water. The land classes must reflect the predicted land–water–crop interaction expected to predominate after irrigation development. This principle of prediction recognizes that irrigation shifts the natural balance, established over time, between water, land, vegetation, fauna, and humans. If land is to be irrigated, it should be permanently productive under the changes anticipated with irrigation.

2.5.3.2 Land Assessment Criteria

The classification system may include several classes of irrigable land and single or several classes of nonirrigable land (based on the limitations for irrigation).

The degree to which lands differ from the optimum state determines their suitability for sustained irrigated agriculture. In an ideal system, the best land would produce the highest yields of a wide range of variety of crops with the lowest inputs – Class I is better than Class II, Class II is better than Class III, etc. In a physical land classification survey, one can only make such a differential on the basis of judgment. Otherwise, detail soil survey is necessary.

2.5.4 Process of Land Classification

Land classification for irrigation is a multi-facet process. It begins with the systematic examination, description, and appraisal of land. The next step is to set criteria for classification based on different factors/characteristics, as mentioned earlier. The third, and the final step, is grouping of land according to the criteria.

2.5.5 USBR Land Classification System

In the 1920s and 1930s, the United States Bureau of Reclamation (USBR) introduced modern method of land classification for irrigated land. The USBR classification system is carried out in the context of a project plan and with respect to the land uses defined under the project plan. The system incorporates broad economic considerations from the beginning.

The USBR Reclamation Manual (1951) and subsequent Reclamation Instructions listed several principles of the USBR classification system:

Prediction: The classification should reflect future conditions as they will exist after the project is implemented. This recognizes that changes may occur in relationships between soils, water, and crops as a result of irrigation and land development, and that the classifier should use the classes to reflect whether these changes are likely to be favorable or unfavorable.

Permanent and changeable factors: The classifier should differentiate between permanent factors, such as soil texture, topography, soil depth, etc., and changeable factors, such as nutrient status, water table depth, salinity, pH, etc. Thus the survey and classification are directed to determine which inputs and improvements to changeable factors are cost effective.

Economic correlation: This assumes that a unique relationship can be established during a classification, between physical conditions of the land such as soils, topography and drainage, and an economic measure of the class ranges.

Arability–irrigability: Land that is physically and economically capable of providing a farmer with an adequate standard of living, where water should be available for irrigation, is first classified. Such land is called “arable.” Arable lands constitute areas that demand consideration for inclusion in a plan of development.

Lands that are selected for inclusion in the plan of irrigation development are called "irrigable" lands.

Land classification can not provide the whole information on which development decisions are made. Other factors such as self sufficiency in food, employment generation, development in business, national priority, etc. influence the decision making process.

Relevant Journals

- Landscape and Ecological Engineering
- Applied Soil Ecology
- Geoderma
- Irrigation Science
- Agricultural Water Management
- Agronomy Journal
- European Journal of Agronomy

Relevant FAO Papers/Bulletins

- FAO Soils Bulletin 55 – Guidelines: Land Evaluation for Irrigated Agriculture
- FAO Soils Bulletin 42: Soil Survey Investigation for Irrigation
- FAO Irrigation and Drainage Paper No. 51: Prospects for the Drainage of Clay Soils
- FAO Soils Bulletin 8: Soil Survey Interpretation and Its Use
- FAO Soils Bulletin 19: Soil Survey Interpretation for Engineering Purposes
- FAO Soils Bulletin 29: Land Evaluation in Europe
- FAO Irrigation and Drainage Paper No. 53: Environmental Impact Assessment of Irrigation and Drainage Projects
- FAO Soils Bulletin 67 – Agro-ecological assessments for National Planning: The Example of Kenya
- FAO Soils Bulletin 73: Agro-ecological Zoning – Guidelines

Questions

1. What are the factors that influence farm production?
2. Discuss the factors affecting irrigation planning and development in an area.
3. Briefly narrate the irrigation development in Asian countries.
4. What are the positive and negative impacts of irrigation on environment and ecosystem?

5. What do you mean by land classification? What is the importance of land classification?
6. Briefly mention the standards of land classification.
7. What are the processes of land classification? Mention the principle of USBR land classification system.

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Chapter 3
Weather: A Driving Force in Determining Irrigation Demand

Weather and climate are important factors in determining day-to-day and long-term activities in agriculture. Productivity of a crop is a function of number of input variables, out of which weather is most important. Crop water demand in an area is largely determined by weather variables. Rainfall is the leading weather variable that affects agricultural cropping pattern, irrigation planning, and water resources development planning. In addition, climatic forecast can help to reduce human vulnerability to agricultural impacts of climate variability through improved decision making, to either prepare for expected adverse conditions or take advantage of expected favorable conditions.

Crops have their critical and optimum climatic requirements. Analysis of climatic elements is useful for the solution of practical agricultural problems. The climatic information serves not only as guide to the selection of the proper sites for a given crop (or the crop for a given site) but also the most desirable period for sowing and harvesting. After all, yield potential of a crop in a given area is determined by thermal and radiative energy budget. Thus, climatological studies can provide basic information in the deliberation and adoption of agricultural technologies. The above aspects are discussed in greater detail in this chapter.

3.1 Concept of Weather and Climate

The *weather* is the set of all external phenomena in a given atmosphere at a given time. The term usually refers to the activity of these phenomena over short periods (hours or days), as opposed to the term *climate*, which refers to the average atmospheric conditions over longer periods of time (normally 25 years or more). There is a wise saying that the climate is what we expect and the weather is what we get. The major weather/climatic elements important for agriculture are solar radiation, rainfall, maximum temperature, minimum temperature, humidity, sunshine duration, photo-period or maximum possible sunshine hour, night temperature, and wind speed.

M.H. Ali, *Fundamentals of Irrigation and On-farm Water Management: Volume 1*,
DOI 10.1007/978-1-4419-6335-2_3,

3.2 Importance of Weather in Agriculture and Water Management

Weather is a primary determinant of agricultural production. Even under improved management practices, most of the variations in crop yield can be explained by the use of analysis of weather elements.

All crops have their critical and optimum climatic requirements. Analysis of climatology at regional scale is most useful for the solution of practical agricultural problems. Without such analysis, the adoption of farming system or an agronomic technology to an area can not be assured of success. The climatic information serves not only as guide to the selection of the proper sites for a given crop but also as the most desirable period for sowing and harvesting. Since agricultural experimentation is expensive and time-consuming, the climatological information may help a great deal to consider extrapolation of research results to a particular region – having "climatic analogues." Climatic analogues are "areas sufficiently alike with respect to certain major weather characteristics that techniques and materials developed for one area have applications and chance of success when transferred to its climatic counterpart" (Nuttonson 1947). In some cases, the ecological limits of a crop may be imposed by the incidence of pests and diseases, which are often related to micro-meteorological variations.

Yield potential of a crop in a given area is determined by thermal and radiative energy budget. Productivity of plants depends on net carbon dioxide uptake by the shoot, which is influenced by the plant water status, soil nutrient status, ambient air temperature, and the absorption of the photo-synthetically active radiation. Crop water demand of a region is also influenced by weather factors. Thus, climatological studies can provide basic information in the deliberation and adoption of agricultural technologies.

Irrigation needs for crop production depend on the interaction of climatic parameters (that determine crop evapotranspiration, ET) and water supply from precipitation. Sustainable food production depends on the judicious use of water resources, that is, more effective use of water in both irrigated and rain-fed agriculture is essential. Options to increase water use efficiency include the rainwater harvesting, conservation, and proper crop planning based on probable rainfall. This necessitates detail analysis of rainfall, which will help in conjunctive water use planning.

The monsoon rainfall influences agriculture in many ways, and its distribution in space and time determines the strategy for planning of crop production. The parameters such as amount, intensity, distribution of rainfall, and number of rainy days are being used to characterize rainfall. Among them, rainfall distribution has profound effect on performance in rain-fed agriculture. Long-term probability analysis can provide a basis for planning cropping pattern and water management strategy (Ali et al. 2005). For planning an irrigation water supply system, the irrigation water requirement during different months of the year is a function of rainfall deficit in those months. Thus, rainfall deficit information (under different probability or risk) for different areas and periods can greatly help in determining optimum water release from a reservoir or source in accordance with demand. Rainfall prediction under different expectations (or probability) can help farmers in evaluating alternative cropping pattern, selecting best adapted plant species, the optimum time of plowing and seeding, soil–water management planning, planning supplemental irrigation schemes, and selection of appropriate harvest time. The long-term pattern of monthly total rainfall and rainfall intensity is required in many areas of water resource management and engineering design such as for surface drainage system, levee design, flood routing, budgeting optimum water use for optimum crop yield, selecting areas for profitable rain-fed farming, and developing possible means for utilization of excess rain-water (e.g., rain-water harvesting) during monsoon season. It may also help in identification of appropriate crops and cropping sequence that match the water-availability period and ensure increased and stabilized crop production.

The compilation, processing, and analysis of weather information will therefore be helpful in developing strategies to optimize crop production and to introduce effective water management practices.

3.3 Basic Mechanisms of Weather Variability

3.3.1 Sun- Earth Geometry

The planet “Earth” is nearly spherical with a diameter of about 12,700 Km. The earth makes one rotation about its axis every 24 h, and completes a revolution around the sun in a period of 365.25 days approximately. The shape of the earth orbit around the sun is about elliptical in nature (Fig. 3.1). The mean distance of the earth from the sun is 1.5×10^8 Km. On 21st December, the earth is closest to the sun (Winter Solstice in north and Summer Solstice in south), while on 21st June it is most remote (Summer Solstice in north and Winter Solstice in south hemisphere), being about 3.3% farther away. On March 21st and September 21st, the earth is equidistant from the sun (Equinoxes). The earth’s axis of rotation is tilted about 66.5° with respect to its orbital plane around the sun (23.5° with respect to N–S). The spherical shape of the earth, elliptical nature of earth orbit, and the tilted angle of earth’s axis account for distribution of solar radiation, change of length of hours of daylight and darkness, and change of seasons.

Specifically, variation of weather most often results from temperature differences from one place to another, and the temperature variation results from the intensity of solar radiation. On large scales, temperature differences occur because areas closer to the equator receive more energy per unit area from the sun than that of the regions closer to the poles. On local scales, temperature differences can occur because different surfaces have different physical characteristic such as roughness, reflectivity, and/or moisture. Surface temperature differences in turn cause pressure differences.

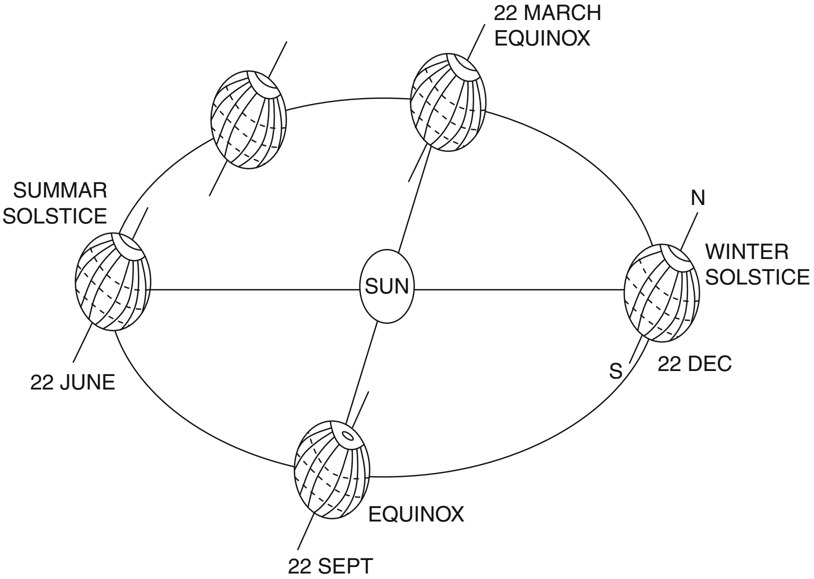

Fig. 3.1 Schematic of earth orbit around the sun

A hot surface heats the air above it and the air expands, lowering the air pressure. The resulting horizontal pressure gradient accelerates the air from high to low pressure, creating wind, and the earth's rotation then causes curvature of the flow via "Coriolis effect." The simple system thus formed can then display emergent behavior to produce more complex systems, and thus other weather phenomena.

3.3.2 Role of Monsoon Wind

The word "monsoon" has been derived from the Arabic word "mausim," which means season. Ancient traders plying in the Indian Ocean and adjoining Arabian Sea used it to describe a system of alternating winds, which blow persistently from the northeast during the northern winter and from the opposite direction, the southwest, during the northern summer. Monsoon is caused by land–sea temperature differences due to heating by the sun's radiation. In winter, the continental landmass cools rapidly resulting in extremely low temperatures over central Asia. As temperature drops, atmospheric pressure rises and an intense high pressure system (anticyclone) develops over Siberia. Cold air flows out of Siberia as north-westerlies and turns into north-easterlies on reaching the coastal waters of China before heading toward Southeast Asia. From time to time, strong outbursts of cold air interact with low pressure atmospheric systems and cyclonic vortices are formed near the equator resulting in strong winds and heavy rainfall to east coast states of Peninsular Malaysia as well as the west coast of Sarawak in East Malaysia.

In summer, intense solar heating leads to scorching temperatures over the Asian landmass. As hot air expands and rises upwards, a semi-permanent low-pressure area develops. Moist south-easterlies originating from the southern Indian Ocean and the Indonesian – Australia region transforms into south-easterlies on crossing the equator and flows across Southeast Asia (causing heavy rainfall) before converging toward Indochina, China, and Northwest Pacific.

3.3.3 Interaction Between Atmosphere, Ocean, and Land Surfaces

Year-to-year climate variations are influenced by interactions between the atmospheric and its underlying ocean and land surfaces. Although the atmosphere fluctuates quite rapidly, surface characteristics such as sea surface temperature (SST), snow cover, and soil moisture change more slowly and are capable of influencing climate over longer periods. In particular, the global climate system interacts strongly with spatial patterns of surface temperatures of the tropical ocean basins, such as those associated with El Nino-Southern Oscillation (ENSO). The ENSO refers to shifts in SSTs – Ẽl Ñino when warmer than normal and La Nina when colder than normal – in the eastern equatorial Pacific, and coupled shifts in barometric pressure gradients and wind patterns in the tropical Pacific (the Southern Oscillation). Although the ENSO phenomenon occurs within the tropical Pacific, its effects can be felt through much of the globe, where it sometimes accounts for a substantial portion of year-to-year variability of the climate.

3.4 Weather Factors Determining/Influencing Crop Water Demand

Weather elements influence crop ET, and hence crop water demand. The ET depends upon several weather elements such as temperature, humidity, solar radiation, sunshine hour, wind speed, etc. Crop water demand is also influenced by rainfall. The weather elements affect ET in the following ways:

3.4.1 Temperature

Warming causes drier air and hence more ET. Increase in temperature affects ET primarily by increasing the capacity of air to hold water vapor and potential gradient.

3.4.2 Humidity

Humidity is a measure of water vapor in the air. The vapor pressure deficit of the air measures its dryness. When the air is dry (i.e., relative humidity is low), more ET is likely to occur. Saturation pressure increases exponentially with increasing temperature. An increase in relative humidity would have the opposite effects.

3.4.3 Solar Radiation

Increased solar radiation (as a result of decreased cloudiness) would increase ET. An increase in cloudiness (caused by increased evaporation and ET) would have the opposite effects.

3.4.4 Wind Speed

Because of ET, the air surrounding the crop canopy becomes close to saturation. The process of vapor removal depends, to a large extent, on wind and air turbulence, which transfers large quantities of air over the evaporating surface. Higher wind speed can increase ET, depending upon the other weather factors, humidity and the plant/crop characteristics, particularly stomatal resistance. Increase in wind speed could also results in higher dust content in the atmosphere, which in turn leads to lower incoming solar radiation.

3.4.5 Sunshine Hour

There is a relationship between sunshine hour and incoming solar radiation. If the other weather factors remain unchanged, the increased sunshine hour likely to increase net solar radiation and hence, contribute to more ET.

3.5 Weather Elements Affecting Agriculture and Crop Production

Agriculture is the most weather dependent of all human activities, particularly in harsh environment. The productivity of a crop depends on genotype × environment interaction. The major weather elements affecting plant growth and crop production are described below.

3.5.1 Solar Radiation

Agriculture is an exploitation of thermal and radiative energy. There is a linear relationship between solar radiation and dry matter production. Solar radiation affects many physiological processes, particularly photosynthesis.

The light requirement varies with plant species. In general, C_4 plants such as maize and sugarcane are most responsive to increased radiation than C_3 plants. There are critical stages of plant growth when solar radiation is especially important. Yoshida (1977) has shown that the critical stage in rice is the 25-day period before flowering when the number of spikelets is determined. The spikelet number accounts for 60% of the yield variation. Lee (1978) has found that the solar radiation during the third month of maize plant's growth or the grain filling period is extremely important for grain yield. Crop response to fertilizer application is intimately related to the climatic environment of energy and water. In a climate where the potential photosynthesis is limited, the efficiency of fertilizer application is also diminished.

3.5.2 Air Temperature

Temperature influences the physio-chemical reactions of the plants and thus their biological activities, rate of development, length of vegetative period, and biomass production. Temperature regulates respiration and translocation of plant. Respiration rate increases with temperature. Each plant has its optimum temperature for each growth stage. There is also a critical temperature (maximum or minimum) below or above which the plant growth or life cycle is hindered. Extreme air temperature affects the physiology of crops. According to Sys (1985), rice grows well when mean temperature varies between 20 and 38°C, with ideal temperature between 30 and 32°C. Performance is marginal if temperature is below 18°C.

Temperature has a more complex relationship to the development of plants, since there is usually an optimum value for each process in plant system. Perhaps the most important effect of high temperature is that it shortens the ripening period in most grain crops and thus reduces the yield. Both photosynthetic and development are very slow at 10°C and both reach their maximum rate at 30–33°C. Photosynthesis is governed by leaf temperature during daylight only, whereas development rate is a function of temperature over the whole day. Experimental work at International Rice Research Institute (IRRI) has shown that the optimum temperature for the ripening of rice is 21–22°C. At temperature below 21°C, translocation is usually decelerated, while at temperature above 22°C, the respiration rate is accelerated and the grain-filling period is shortened. Gomosta and Vergara (1988) found that internode elongation of deepwater rice increased as temperature increased from 15 to 30°C, then decreased at 35°C. At a temperature as high as 33°C, groundnut hardly produces any pods as a result of reduced production of pollen, short-lived flowers, and the occurrence of dormant ovaries (Chang 1981).

3.5.3 Rainfall

Rainfall amount, intensity, and its distribution determine the cropping pattern in a region. It also determines the irrigation need for successful crop production.

3.5.4 Air Humidity

The air humidity (water vapor content of the air) is important for the crop. It influences the inner water balance of plants by restricting the transpiration exchanges, and affects the plant physiology. It affects the radiation balance and tends to reduce the daily temperature ranges. High relative humidity favors crop growth through the vegetative stage. During grain formation, low humidity may cause grain to shrink, but high humidity favors disease, particularly in rain-fed rice. In rice, relative humidity may affect grain formation after milk stage, ripening. Humidity is particularly important in the field of plant protection because disease incidences of plants are favorably influenced by the high relative humidity.

3.5.5 Wind

Frequent violent windstorm is another important factor that determines the adaptability of a region to certain crops, such as banana, citrus, etc. Mild wind can help pollen fertilization of plants. The average solar radiation intensity in the windward side is generally 20–30%, which is lower than that of the leeward side. Strong winds in the windward areas decrease both photosynthesis and translocation. Wind may transport sands to the vegetative surface of plants, which is harmful.

3.5.6 Photoperiod or Day-Length

Photoperiod is important in crop development. In case of photo-sensitive crop cultivars, photo-period can cause crop failure and hinder the introduction of new varieties. For the same amount of daily solar radiation, the photosynthetic rate increases with day length. Flowering of soybean is rigidly controlled by day length. Leihner and Cock (1977) have found that when the day-length was artificially shortened to 11.5 h, rice yield decreased from 5.7 to 4.7 t/ha during the wet season and from 4.3 to 3.8 t/ha during the dry season.

Another effect of day length is that certain crop varieties or species simply do not produce a high yield if the photo-period is too long or too short. If a photo-sensitive jute variety is sown before February 28 at different parts of Bangladesh, it produces flower at early stage due to shorter photo-period, thus reduces fiber yield.

Effect of climatic factors on growth and development of plant is dependent on various growth phases:

- Germination – Agronomical research has indicated a temperature dependence of germination time. Each crop has a unique critical temperature and temperature sum, which are related as follows.

  When a crop requires a temperature sum of, for example, 150°C and a critical temperature of 10°C, it will germinate in 15 days when the temperature is 20°C, but in 10 days when the temperature is 25°C. When the temperature sum exceeds the threshold value, the germination process is complete.
- Initial spread – In this phase, the crop does not cover the field yet. The growth of the crop is dependent on leaf area index (LAI), which in turn is linearly dependent on crop biomass. But the captured solar radiation depends on LAI. As a result, crop growth in this phase is exponential.
- Total coverage of field – In this phase, growth is assumed to be linearly dependent on incident light and respiration rate, as nearly 100% of all incident light is intercepted. Typically, LAI is above two to three in this phase. This phase of vegetative growth ends when the plant gets a certain environmental or internal signal and starts reproductive growth (as in cereals and pulses) or the storage phase (as in tubers).

3.6 Definition, Measurement, and Analysis of Weather Variables

3.6.1 Rainfall

The source of all water on the earth is precipitation in the form of rainfall, snow, hail, frost, and dew. Rainfall is measured at a point. Therefore, data are applicable to that site only. Generally, it is recommended to extrapolate results without adjustment from the point site to a small area around the gauge, say upto 4 km^2.

3.6.1.1 Formation of Rain

Water evaporates from various sources such as oceans, rivers, lakes, ponds, crop fields, and plants. The water vapor is accumulated in the atmosphere over time. This vapor is cooled with some mechanisms, become saturated (or close to saturation) and with the presence of some condensation elements (condensation nuclei, over which the vapor is condensed) the vapor is condensed enough to form raindrops.

The cooling of water vapor may be accomplished by several processes or mechanisms:

Orographic Barrier

Because of orographic barrier (such as hilly areas, mountain), large scale air mass is lifted to higher atmospheric zone or elevation where the temperature is low. As a result, the water vapor becomes cold.

Uneven Heating of the Earth Surface

Because of unequal solar radiative energy (due to latitude), the earth surface is heated unevenly. Besides, the heat absorbing capacity of different surfaces is not same. For example, the concrete structure is heated rapidly than the land or water surface. When the air is heated, it is expanded, becomes lighter and rises up. In an undisturbed free atmosphere, the temperature of the air decreases with the increase in height or altitude (known as temperature lapse rate). The expanding air mass drops its temperature approximately at the rate of 10°C per km of rise up. This rate of temperature fall is higher than the normal lapse rate. As the cooling of the water vapors continues, it starts to condense, which is known as cloud. At further cooling, the condensed vapor start to condense or freeze on or around the condensation nuclei.

The *condensation* or *freezing nuclei* are the elements on which water droplets or crystals are formed. These are small diameter (0.1–10 μm) particles of various substances such as clay minerals, carbon dioxide (CO_2), different salts, silver iodide (AgI), etc. Condensation tends to enlarge droplets or ice crystals.

In general, the droplets are so small in weight that the normal upward motion of air is sufficient to retard their downward motion. Generally, the droplets of cloud are of 10-μm diameter, and an upward flow of air having 0.5 cm/s velocity is sufficient to retard their fall. Under favorable condition, the droplets and crystals increase in diameter until they can stay at upper atmosphere. When their falling speed exceeds the upward speed of air, the rainfall occurs.

3.6.1.2 Rainfall Pattern

Rainfall has temporal (variable with time) and spatial (variable with space) pattern.

Temporal Pattern

In nature, a wide range of patterns are possible. Some rain storms have their peak intensity occurring toward the end of the storm period, and a large number have

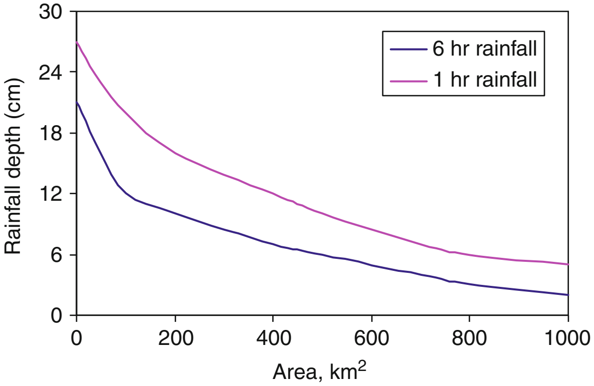

Fig. 3.2 Typical depth-area-duration curve of rainfall

a tendency for the peak to occur more or less centrally. However, the most commonly occurring time of peak is partly related to the duration of the storm rainfall.

Spatial Pattern

A depth-area curve of rainfall expresses graphically the relation between a progressively decreasing average depth of rainfall over a progressively increasing area from the center of the storm outwards to its edge (Fig. 3.2). It is used in estimating probable maximum rainfall in an area.

3.6.1.3 Rainfall Analysis

Averaging Catchment Rainfall

There are three ways to estimate catchment average rainfall: Arithmetic average, Thiessen weight, and Isohyetal weight.

(a) *Arithmetic average*

According to this method, the mean rainfall depth (P) is:

$$P = (P_1 + P_2 + \dots\dots\dots + P_n)/n. \tag{3.1}$$

Where $P_1, P_2, \dots P_n$ are the rainfall depth at station 1, 2, ... n, respectively; and n is the total number of station.

Merits

It is the easiest procedure

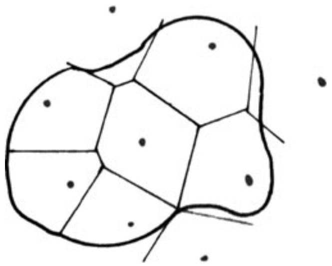

Fig. 3.3 Schematic presentation of Thiessen polygon

When the rain gauges are uniformly distributed over the catchment and the individual readings are not differed too much from the mean, this method is suitable for determination of average rainfall over the catchment.

Demerits

Least accurate procedure

Difficulties arise if the rainfall is not uniform due to orography and if the recording sites are not evenly distributed across the catchment.

(b) *Thiessen weights or Thiessen polygon*

This method uses the concept of a right angle bisector (Fig. 3.3). The procedure is reasonably accurate and objective. The average rainfall is calculated as:

$$\mathrm{P} = (\mathrm{P_A}.\,\mathrm{W_A}) + (\mathrm{P_B}.\,\mathrm{W_B}) + (\mathrm{P_C}.\,\mathrm{W_C}) + \ldots \qquad (3.2)$$

where P is the mean rainfall; $\Sigma W_{\mathrm{i}} = 1$, W_{i} is based on proportional area; $W_{\mathrm{A}} = A/(A + B + C + \ldots)$; P_{A}, P_{B}, P_{C}, … are the rainfall for the area A, B, C, …, respectively.

Merits

Accurate than the arithmetic average method
Gives reasonable estimate of mean rainfall

Demerits

- More complex than the arithmetic average method
- requires skill and judgment of the personnel
- requires knowledge of the area

(c) *Isohyetal weight*

Isohyetes are lines of equal rainfall depth drawn over a map of the catchment. Isohyetes are drawn to take into account orographic effects (Fig. 3.4). The mean rainfall is calculated using the following formula:

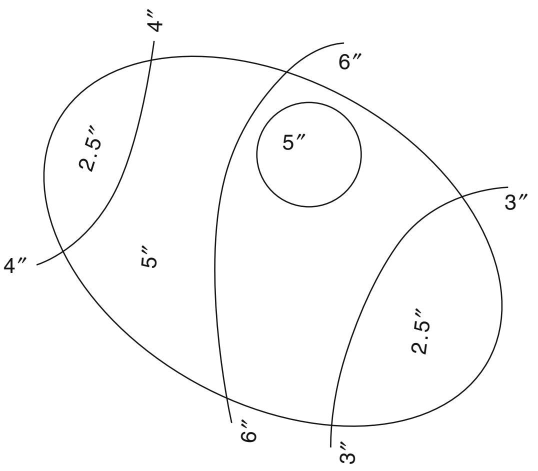

Fig. 3.4 Schematic presentation of Isohyetal method

$$P = \frac{\sum P_i A_i}{\sum A_i} \tag{3.3}$$

where P is the mean rainfall for the catchment, P_i is the mean rainfall depth between adjacent isohyetes or isolines (lines of equal rainfall), and A_i is the area between the same adjacent isolines.

Merits

It is a subjective method.
Gives better estimate than the arithmetic average method

Demerits

Some experience is required
Knowledge of the area is involved in this method.

3.6.1.4 Rainfall Indices

Rainfall Distribution Coefficient

Rainfall distribution coefficient is defined as the ratio of maximum rainfall at a point concerned to the mean rainfall on the basin. A higher value of distribution coefficient means that rain is less uniformly distributed over the basin. For a given rainfall amount, the greater the distribution coefficient, the greater the peak runoff.

Rainfall Distribution Index (RDI)

Basavaraju and Joishi (2000) proposed an index called rainfall distribution index (RDI), to study water availability in relation to crop management. For monthly estimation,

RDI = [Monthly rainfall (mm)/Total number of days in the month] × (No. of rainy days in the month)

Effective Rainfall

Effective rainfall is defined as the part of total rainfall that is effectively used by the crop, or in any other intended use. It is the amount that is retained or used after rainfall losses due to surface runoff and deep percolation. For crop field, it is the rainfall ultimately used to determine the irrigation requirement of the crop.

More details regarding the method of determining effective rainfall has been described in Chap. 7 (*Field Water Balance*).

3.6.1.5 Rainfall Data Checking and Gap Filling

Data Checking for Error

Before use, all data should be checked for potential errors, especially inconsistencies. To identify in-homogenities for long-term rainfall data, a double mass curve analysis is used.

Mass curve of rainfall is the plot of cumulative rainfall of a station vs. time. In double mass curve method, cumulative station data vs. sum of cumulative data at nearby (base) stations is plotted. Approximately 10 base stations are used and normally annual data are used. Fluctuations may occur, so more than 5 points are needed before a change is accepted. Figure 3.5 shows a typical double mass curve of rainfall.

Fill Up of Short Gaps in Daily Rainfall

Rainfall data are required for hydrological, crop water requirement, irrigation planning purposes, and in crop growth models. Because of different unavoidable reasons (instrument failure, absence of personnel, etc.), data may be unavailable for some period. An estimate of data for that period is required. Short gaps are filled in by comparing the mean value of the station in question with the nearby stations. If the difference of means with nearby stations is not greater than 10%, rainfall is estimated by the following formula:

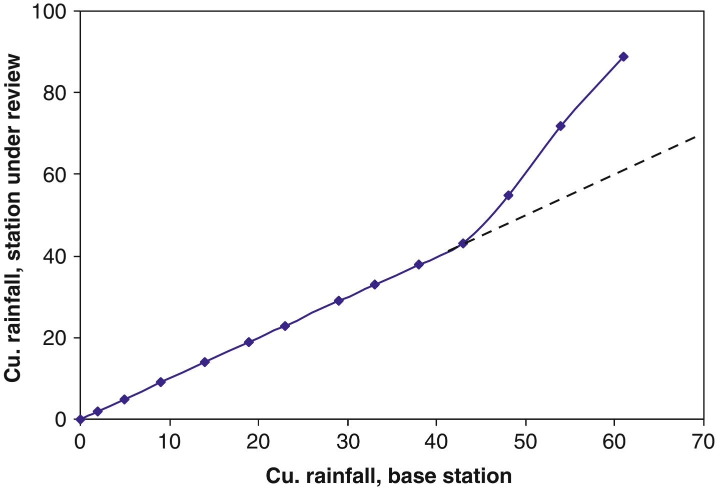

Fig. 3.5 Double mass curve of rainfall

$$\mathrm{U_x} = \frac{1}{K}\left(\frac{\bar{P}_x}{\bar{P}_1}P_1 + \frac{\bar{P}_x}{\bar{P}_2}P_2 + \ldots\ldots + \frac{\bar{P}_x}{\bar{P}_k}P_k\right) \tag{3.4}$$

where U_x is the estimated rainfall at station X, $\bar{P}x$ is the mean rainfall at station X, $\bar{P}_1, \bar{P}_2, \ldots, \bar{P}_k$ are the mean rainfall at nearby stations, $P_1, P_2, \ldots, P_\mathrm{k}$ are the rainfall at nearby stations for the missing period. The method is referred as normal ratio method.

Estimation of Missing Data Using Regression Technique

The missing data can also be estimated through multiple regression using computer, in the form:

$$\mathrm{P = a_0 + a_1P_1 + a_2P_2} + \ldots \tag{3.5}$$

where P is the rainfall of the targeted missing station for the available data period; P_1, P_2, ... are the rainfall of the nearby stations for the same period; a_0 is the intercept, and a_1, a_2, ... are the coefficients. These coefficients are to be used for estimating rainfall for the missing period.

Extending Rainfall Data

For example, there are n_1 years of concurrent annual rainfall at stations X and Y, and station X has a further n_2 years of data. The objective is to extend the annual rainfalls at Y to n_1+n_2 years. First, we have to establish:

$$\mathrm{Y} = \mathrm{a} + \mathrm{bX}$$

where a, b are determined by least squares for the concurrent data sets. Then the above equation is used to compute the values over n_2.

For seasonal or monthly data, establish a separate equation for each month or season.

3.6.1.6 Rain Gauge Networking

The areas having similar rainfall depth are referred to as homogeneous rainfall area. But in real world, the rainfall amount varies spatially. The difference is prominent for hilly areas. The variability of rainfall can be captured by installing sufficient number of rain gauges. The density of rain gauge can vary considerably. In selecting the rain gauge number, the cost involvement (installation and maintenance) and easiness of transportation for the visitors should be considered in addition to the required accuracy. The minimum density of rain gauge required for different arial consideration as per guideline of World meteorological Organization are as follows:

1. For arid and polar region, the minimum density may be one station per 10,000 km^2.
2. For mountainous regions of tropical and temperate Mediterranean, one station per 100–1,200 km^2.
3. For flat regions of temperate, Mediterranean, and tropical regions, one station per 600–900 km^2. For problem areas (lack of fund, communication), the density may be reduced to one station per 600–2,500 km^2.

On the basis of the concept of probability and statistics, certain number of rain gauge stations is necessary to obtain average rainfall with a certain percentage of error. If it is required to reduce the allowable error, more number of gauges is required and vice versa.

Let N is the optimum number of rain gauge, C_{v} is the coefficient of variation of rainfall based on existing rain gauges, and E is the allowable percentage error in estimating mean rainfall. Then

$$N = \left(\frac{C_v}{E}\right)^2, \tag{3.6}$$

where $C_{\mathrm{v}} = 100 \times$ standard deviation/mean.

3.6.1.7 Examples on Rainfall Data Analysis

Example 3.1 In a catchment, rainfall is recorded at four stations. At the stations, the rainfall amounts in a year are 1,025, 1,100, 950, and 1,200 mm; and the area of influence under the stations are 100, 150, 200, and 220 ha, respectively. Calculate the mean rainfall over the catchment using:

(a) Arithmetic average
(b) Thiessen approach

Solution We know, mean rainfall by arithmetic average = $\Sigma P_i/N$
And by Thiessen approach, mean rainfall = $\Sigma A_i P_i/\Sigma A_i$
The calculation summary are given below:

Station no.	Rainfall, R(mm)	Area of influence, A(ha)	$R \times A$
1	1,025	100	102,500
2	1,100	150	165,000
3	950	200	190,000
4	1,200	220	264,000
Sum	4,275	670	721,500

Thus, mean rainfall by arithmetic average = 4,275/4 = 1,068.75 mm (*Ans.*)
And, mean rainfall by Thiessen approach = 721,500/670 = 1,076.86 mm (*Ans.*)

Example 3.2 The isohyets of annual precipitation in a basin were drawn. The areas between the isohyets are given below. Calculate the mean annual precipitation over the basin.

Isohyets (cm)	Area between the isohyetes (ha)
80–90	750
90–110	650
110–115	1,000
115–120	1,500

Solution We know, mean precipitation by isohyetal method = $\Sigma A_i P_i/\Sigma A_i$, where A_i is the area between two successive isohyetes i and $i+1$.
The calculation summary is shown in the table given below:

Sl no.	Average depth of successive 2 isohyetes (P_i) (cm)	Area between the isohyets (A) (ha)	$A_i \times P_i$
1	85	750	63,750
2	100	650	65,000
3	112.5	1,000	112,500
4	117.5	1,500	176,250
Sum	415	3,900	417,500

Thus, the mean precipitation = $\Sigma A_i P_i/\Sigma A_i$ = 417,500/3,900 = 107.1 mm (*Ans.*)

Example 3.3 What is the volume of rainfall when 80 mm fall over an area of 4,000 Km^2?

Solution Volume of rainfall,$V = A \times d$
Here, area of rainfall = 4,000 Km^2= 4,000 × (1,000 × 1,000)m^2= $4 \times 10^9 \text{m}^2$
Depth of rainfall = 80 mm = 80/1,000 = 0.08 m

Thus, $V = (4 \times 10^9\ \mathrm{m}^2) \times 0.08\ \mathrm{m}$
$= 32 \times 10^7\mathrm{m}^3$(*Ans.*)

Example 3.4 The normal annual rainfall at five stations A, B, C, D, and E in a catchment are 100, 80, 95, 105, and 90 cm, respectively. In the year 2005, the station B was inoperative and the stations A, C, D, and E recorded annual precipitation of 90, 95, 90 and 85 cm, respectively. Estimate the rainfall at station B in that year.

Solution Here, the normal yearly rainfall (N_i) and annual precipitation (P_i) are:

$N_\mathrm{A} = 100$	$P_\mathrm{A} = 90$
$N_\mathrm{C} = 95$	$P_\mathrm{C} = 95$
$N_\mathrm{D} = 105$	$P_\mathrm{D} = 90$
$N_\mathrm{E} = 90$	$P_\mathrm{E} = 85$
$N_\mathrm{B} = 80$	$P_\mathrm{B} = ?$

From normal ratio method, rainfall at station B,

$$P_\mathrm{B} = (N_\mathrm{B}/N)\,[P_\mathrm{A}/N_\mathrm{A} + P_\mathrm{C}/N_\mathrm{C} + P_\mathrm{D}/N_\mathrm{D} + P_\mathrm{E}/N_\mathrm{E}]$$

Here, number of station other than B, $N = 4$
Putting the above values, rainfall at station B in 2005, $P_\mathrm{B} = 74.0$ cm (*Ans.*)

Example 3.5 A catchment has four rain gauge stations. In a year, the annual rainfalls recorded by the gauges are as follows:

Station	A	B	C	D
Rainfall (cm)	120	105	110	112

For an 8% error in the estimation of the mean rainfall, find out the optimum number of stations in the catchment. How many additional rain gauge stations are required to reduce the error to 5%?

Solution Mean of the stations rainfall,

$$P_\mathrm{mean} = \sum P_\mathrm{i}/N = 103.0\ \mathrm{cm}.$$

Standard deviation of the rainfall,

$$\mathrm{SD} = (1/(N-1)) \sum \sqrt{}(P_\mathrm{i} - P_\mathrm{mean})^2 = 19.65\ \mathrm{cm}.$$

Coefficient of variation,

$$\mathrm{CV} = 100\ (\mathrm{SD}/P_{\mathrm{mean}}) = 19.07\%.$$

Given, error in mean rainfall, $E = 8\%$
The optimum number of rain gauge for this catchment,

$$N = (\mathrm{CV}/E)^2 = (19.07/8)^2 = 5.7 \approx 6 \text{ nos } (\textit{Ans.}).$$

To reduce error to 5%,

$$N = (\mathrm{CV}/E)^2 = (19.07/5)^2 = 14.5 \approx 15.$$

Existing number of stations = 4
Thus, additional rain gauge stations required = 15 − 4 = 11 nos (*Ans.*)

3.6.1.8 Probability Aspects of Rainfall

Concept of Probability

In our everyday life, we use the notion – "probability." Simply speaking, it is the chance of occurrence of an event. It is a mathematical basis for prediction. For an exhaustive set of outcomes, the probability of an event is the ratio of the outcomes that will produce a given event to the total number of possible outcomes. If we consider a coin having two sides – side-1 (head) and side-2 (tail), and toss it in an unbiased manner, the coin can land either side-1 up or side-2 up. That is, the possibility or probability of either side-1 or side-2 is obviously 50% (possible outcome of side-1/total number of possible outcome = 1/(1+1) = 0.50 or 50%).

The concept of probability can be applied in different aspects of rainfall. Rainfall record of every station is a point of observation of rainfall. Regarding rainy days, it can be expected that there will always be some dry and wet days, and hence the dry-day or wet-day probability. Other forms of probability include depth of rainfall, frequency of occurrence of events (may be of particular depth or duration), etc. Probability is usually denoted with "P," so that probability of an event x is simply P(x). It is expressed either as a decimal (≤ 1.0) or percentage by multiplying the decimal by 100.

Some Related Terminologies

Exceedance Probability

It denotes the probability that a given rainfall event (or a given magnitude of flood discharge) will be exceeded within a certain period of time.

Annual Exceedance Probability (AEP)

Annual exceedance probability (AEP) is the probability of exceedance of a given event within a period of one year. Probability of non-exceedance $= 1 -$ probability of exceedance

Risk

Risk is synonymous with exceedance probability. It is the probability of the occurrence of an undesirable event in a given number of observations.

Probable Maximum Rainfall

The probable maximum rainfall is defined as the theoretically greatest depth of rainfall for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year.

Average Recurrence Interval (ARI)

Average recurrence interval (ARI) is the average or expected value of the period between exceedance of a given event (e.g., rainfall, flood). The average frequency or recurrence interval does not imply periodicity. A 10-year frequency rain means that a rain that occurs on an average once in 10 years, for example, 10 times in 100 years or 20 times in 200 years. It is not necessary that such a rain occurs only after 10 years; it may occur during four consecutive years and then not occur for 20 years.

Return Period

It is synonymous with recurrence interval. It is the average period in years within which an event (rainfall or flood) of specified magnitude will be equaled or exceeded.

Dependable Rainfall

This is defined as the amount of rainfall that can be depended upon in 1 out of 4 or 5 years corresponding to a 75% or 80% probability of exceedance, and thus representing a dry year. The dependable rainfall (80%) is used for the design of the irrigation system capacity.

Rainfall in Wet, Normal, and Dry Years

Rainfall in wet, normal, and dry years is defined as the rainfall with a 20, 50, and 80% probability of exceedance, respectively (representing a wet, normal, and dry year).

Establishing Rainfall Probability Graph

The following steps are to be followed to draw a rainfall probability graph:

1. Rank annual (or monthly) data series in descending order (largest to the smallest value) – largest rank 1.
2. Calculate plotting position (probability value for each data point), p, using one of the following method:
   (a) Weibull's method, $p = m/(2n+1)$
   (b) Gringorten's method, $p = (m - 0.44)/(n+0.12)$

where n is the number of records and m is the rank number.

3. The probabilities thus found are to be plotted on probability paper as trial and error method. Try on both normal and log-normal probability paper. Rainfall is on ordinate and probability is on abscissa as a normal probability scale. The distribution (normal or log-normal) at which a given data set suits, points are found to approximate a straight line. Accept that distribution or probability graph.
4. Draw a straight line through the data points (following least square principle).

Now from the straight line, find the rainfall amount for a particular probability level of exceedance, or the probability of exceedance for a particular rainfall amount. The yearly value at 80%, 50%, and 20% probability (P_{80}, P_{50}, and P_{20}) represents the dry, average, and wet year, respectively.

Monthly values of rainfall for the dry year can be estimated from the yearly values according to the following relationship:

$$P_{\mathrm{idry}} = P_{\mathrm{iav}} \times \frac{P_{\mathrm{dry}}}{P_{\mathrm{av}}}, \tag{3.7}$$

where P_{idry} is the average rainfall for month i of the dry year, P_{iav} is the average monthly rainfall for month i, P_{dry} is the yearly rainfall at 80% probability of exceedance, and P_{av} is the average yearly rainfall.

Similarly, monthly values of rainfall for the wet year can be determined from the yearly values as:

$$P_{\mathrm{iwet}} = P_{\mathrm{iav}} \times \frac{P_{\mathrm{wet}}}{P_{\mathrm{av}}}, \tag{3.8}$$

where P_{iwet} is the average rainfall for month i of the wet year, P_{iav} is the average monthly rainfall for month i, P_{wet} is the yearly rainfall at 20% probability of exceedance, and P_{av} is the average yearly rainfall.

Probable Seasonal Rainfall

Using the plotting position method of frequency analysis, the seasonal rainfall vs. the probability of exceedence at any location can be established. As Fig. 3.6 shows,

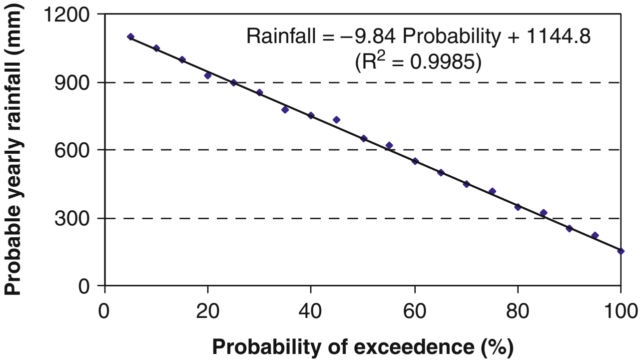

Fig. 3.6 Schematic presentation of probable seasonal rainfall

the seasonal rainfall (R) at any probability of exceedence (P_e) expected to be equal to *or* more than the value given by the following equation:

$$R(P_e) = -9.84\ P_e + 1144.8,$$

where $R(P_e)$ is seasonal rainfall at exceedence probability of P_e.

Software Tools for Probability Analysis

Now-a-days, different softwares are available for rainfall probability analysis (e.g., Rainbow). In addition to rainfall for a particular probability, return period, etc. can be obtained with these tools.

Probability Under Different Perspectives

Probability of occurrence of a rainfall or flood having a recurrence interval of T years, occurring in any year (the chance of its occurrence in any one year) that is the probability of exceedance, is:

$$P = \frac{1}{T}.$$

Probability of no T year rainfall occurring in any year (probability of non-exceedance) $= 1 - P = 1 - 1/T$

Probability of no T year rainfall occurring in N years $= (1 - 1/T)^N$

Probability of at least one T year rainfall occurring in N years $= 1 - (1 - 1/T)^N$

Example 3.6 Suppose we have an agricultural field protected from the adjacent river by a levee, which is designed to retain the one in 100 floods.

(a) What is the chance of the field being flooded in the next 25 years?
(b) If we wish to lower the risk to 1%, what ARI flood should the levee be designed for?

Solution (a) Chance of the field being flooded in the next 25 years is

$$\begin{aligned} P &= 1 - \left(1 - \frac{1}{T}\right)^N \\ &= 1 - \left(1 - \frac{1}{100}\right)^{25} \\ &= 22\%. \end{aligned}$$

i.e., approximately a one-fourth chance.

(b) $0.01 = 1 - (1 - 1/T)^{25}$
or $T = 2{,}500$ yrs

Example 3.7 (a) What is the chance in any year of a wetland being flooded from an adjacent river, which has a natural levee that is overtopped on average once in every 5 years?
(b) In the next 5 years, what is the chance of the wetland not being flooded?

Solution (a) ARI, $T = 5$ years
AEP $= 1/T = 1/5 = 0.2 = 20\%$ chance of the wetland being flooded in any year.
(b) $P = 1 - (1 - 1/T)^5 = 67\%$ of the wetland being flooded in the next 5 yrs.
Therefore, there is a $(1 - 0.67) = 33\%$ chance of the wetland not being flooded in the next 5 yrs.

3.6.1.9 Peak Flow/Runoff Estimation from Rainfall Data

Peak discharge is the maximum rate of flow of water passing a given point during or after a rainfall event. Runoff from rainfall depends on various factors such as rainfall characteristics, meteorological characteristics, basin size and its characteristics, soil characteristics, channel characteristics, etc. Peak runoff is usually determined using rational method and SCS curve number method.

Rational Method

At the early stage of development, this method was used in urban catchments, but now it is also used in rural areas. Conceptually, the rational method of estimating peak flow on small watershed (<12 km^2) is based on the criterion that for storms of uniform intensity, distributed evenly over the basin, the maximum rate of runoff occurs when the entire basin area is contributing at the outlet and this rate of runoff is equal to a percentage of the rainfall intensity. This method is used to estimate peak flow for designing small structure like culvert.

According to rational method, peak flow is computed using the relation:

$$Q = fCIA, \tag{3.9}$$

where Q is the peak flow rate (m^3/s), C is the dimensionless runoff coefficient, I is the average rainfall intensity (mm/hr), A is the area in km^2 or ha, and f is the conversion factor (0.278 if area is in km^2 and 0.00278 if area is in ha).

The runoff coefficient varies with the surface condition. For given storm events of same rainfall intensity, nonconstant coefficients of runoff are obtained. The variation is due to the different antecedent moisture conditions. For loose soil (high infiltration) its value is low (0.3−0.6) whereas for hard surface its value may be up to 0.8.

3.6.1.10 Flood Hydrograph and Unit Hydrograph

A graph of the time distribution of runoff from a catchment is termed as hydrograph. In various purposes, the amount and timing of runoff from rainfall events are needed. Obviously, the amount and timing of runoff from different rainfall events are different from each other. Various forms of rainfall–runoff relations are used: flood hydrograph, unit hydrograph, etc. Flood hydrograph (or discharge hydrograph or runoff hydrograph) is the graphical display of runoff (from a catchment or drainage basin) vs. time from the start of rain. In response to a rainstorm, the quantity of water flowing in a stream increases, reaches to its peak, and then starts to decline (Fig. 3.7). In the hydrologic analysis for a drainage structure, it must be recognized that there are many factors that affect runoff or flood. These include drainage basin characteristics (shape, size, slope, vegetation, storage, etc.), rainfall

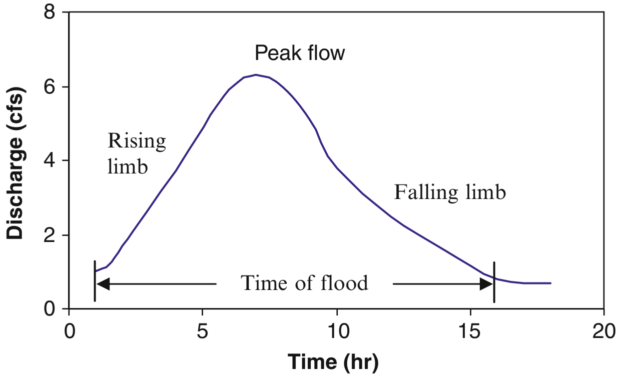

Fig. 3.7 Typical flood hydrograph

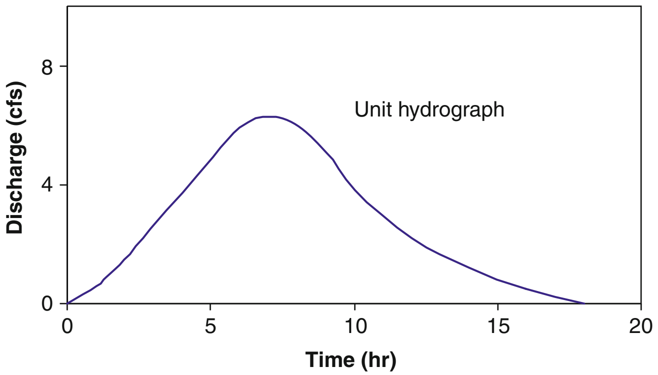

Fig. 3.8 Typical form of a unit hydrograph

characteristics (intensity, duration, distribution characteristics), and stream channel characteristics (geometry, slope, natural and/or artificial control, roughness, etc.).

Unit Hydrograph

Unit hydrograph is the graphical display of the amount of runoff from 1 in. (or 1 cm) of rainfall excess (i.e. 1 in. of direct runoff from over the basin area) (Fig. 3.8). The steps for developing a unit hydrograph from a single storm hydrograph are as follows:

- Separate the baseflow by analyzing the flood hydrograph
- Measure the total runoff volume of direct runoff and convert this to inches (or centimeter) over the basin
- Divide the ordinates of the direct runoff hydrograph by the runoff volume (in inches or cm) and plot this against time

3.6.2 Solar Radiation

3.6.2.1 Basics of Solar Radiation and Its Classification

Emission of Radiation

The sun produces its energy by nuclear fusion, where two atoms of Hydrogen are fused to form one atom of Helium and large amount of energy is released. The process occurs at extreme temperatures and pressures, and according to the laws of thermodynamics, radiation is emitted. Most of the emitted radiations from the sun are at the visual and thermal spectrum. By solar collector, the radiation can either be stored as heat or transformed into electricity.

All substances at a temperature above 0°K (absolute zero) emit radiation. The radiant energy is emitted on different wavelengths and is a function of temperature only. Wavelength is characteristics of maximum emissive power, and therefore proportional to the temperature. The wave lengths of different rays are as follows:

Ultraviolet ray: <0.38 μm
Violet ray: 0.38–0.45 μm
Visible ray: 0.36–0.76 μm
Infrared ray: >0.76 μm

Incidence of Solar Radiation to the Earth

Solar radiation from the sun enters the surface-atmospheric system as short-wave radiation. Because of cloud, gases, and other particles of the atmosphere, about a quarter of the available solar radiation is reflected or scattered back to space before it reaches the ground. A portion of the radiation absorbed by the earth surface is reradiated to the space as long-wave radiation (as the earth is cooler than sun). A part of the long-wave radiation is absorbed by the gases of the atmosphere, and a part is gone to the space (Fig. 3.9).

Classification Solar Radiation on the Earth

Solar radiation on the earth surface can be divided into two components:

1. *Beam or direct radiation:* Radiation that is received from the sun without any change in the direction of radiation is known as beam or direct radiation. On a clear day, about 95% of radiation is beam or direct radiation.

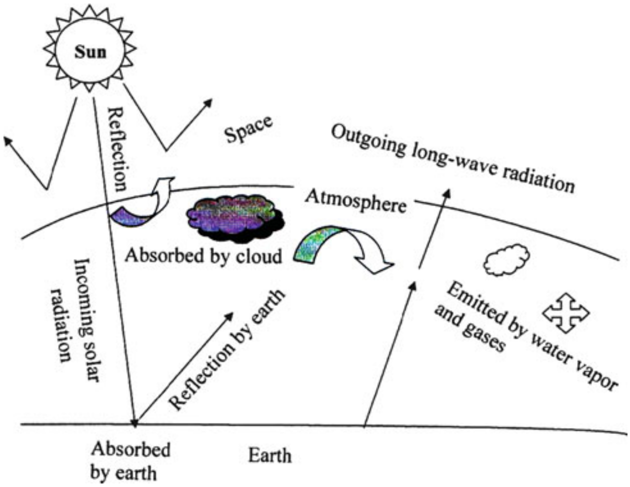

Fig. 3.9 Scattering of incoming solar radiation

2. *Diffuse radiation:* Radiation that reaches the earth surface after a change of direction due to reflection is referred to as diffuse radiation. It comes from all directions. Approximately, 1/5th of the total radiation is diffuse radiation.

3.6.2.2 Some Relevant Terminologies

Angle of Incidence

The angle between the beam radiation and the normal to the plane is termed as angle of incidence. It ranges between 0 and 90°.

Albedo

It is the part of the solar radiation that is reflected to the atmosphere. Albedo is defined as the ratio of reflected energy to the incident energy. It depends on the type and characteristics of the surface, and atmospheric condition (cloud and/or other constituents). For field crops, FAO (1992) suggested an average value of albedo as 0.23. For different surfaces, the values of albedo are as follows:

1. Ice: 0.70–0.80
2. Sand: 0.25–0.40
3. Forest area: 0.15–0.27
4. Smooth water surface: 0.05–0.18

Solar Constant

Because of the elliptical nature of the earth's orbit around the sun, the distance of sun from the earth varies during the year. For this variation, the extra-terrestrial solar radiation reaching outside the earth atmosphere is given by (Duffie and Beckman1980):

$$G_0 = G_{sc}(1 + 0.33\mathrm{Cos}\,(360\mathrm{n}/365)), \tag{3.10}$$

where n is the day of the year (e.g., Jan. 1 = 1, Jan. 10 = 10, Feb.1 = 32, etc.), G_{sc} is the solar constant.

Solar constant is defined as the average amount of radiation that reaches on a unit area of surface per unit time at the top of atmosphere and normal to the direction of sun radiation. It is termed as *constant* because it has more constancy than the incident radiation at the earth surface. According to the measurement of 1971, it was taken as 1,353 W/m^2; but according to the measurement of 1977, it was recommended as 1,373 W/m^2.

Solar Declination

The angular position of the earth at noon with respect to the plane of the equator is known as solar declination. Its range is 0 to ± 23.45°, north is positive. The declination, δ (in degrees) is calculated as (Cooper 1969):

$$\delta^0 = 23.45 \text{ Sin } ((360 \times (284 + \text{n})/365)), \tag{3.11}$$

where n is the day of the year. A plot of declination vs. time of the year is given in Fig. 3.10.

Extraterrestrial Radiation

In the absence of atmosphere, the amount of solar radiation that would reach on a unit area of surface per unit time in the direction of normal to the radiation is termed as extraterrestrial radiation. The extraterrestrial radiation at any location for any time can be calculated as (Smith et al. 1992):

$$R_\text{a} = \frac{24 \times 60}{\pi} \quad G_\text{sc} \,.\, d_\text{r}(\omega_\text{s} \sin\psi \, \sin\delta + \cos\psi \, \cos\delta \, \sin\omega_\text{s}), \tag{3.12}$$

$$= 37.6 \, d_\text{r} \, (\omega_\text{s} \sin\psi \, \sin\delta + \cos\psi \, \cos\delta \, \sin\omega_\text{s}), \tag{3.13}$$

where R_a is the extraterrestrial radiation (MJ $\text{m}^{-2}\text{d}^{-1}$), G_sc is the solar constant (MJ $\text{m}^{-2}\text{d}^{-1}$) = 0.0820, d_r is the relative distance of earth and sun, ψ is the latitude (rad), δ is the solar declination (rad), ω_s is the sunset hour angle (rad).

And,

$$\omega_\text{s} = \arccos(-\tan\,\psi \,\tan\,\delta). \tag{3.14}$$

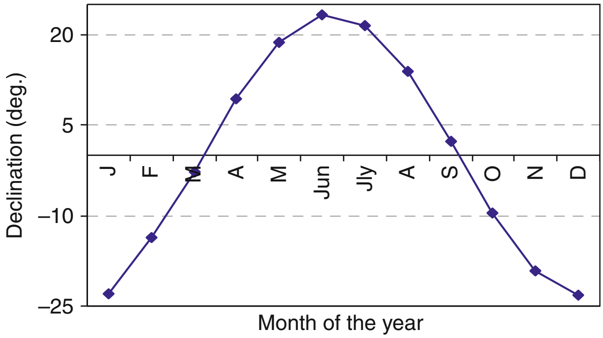

Fig. 3.10 Declination as a function of the time of year

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right), \tag{3.15}$$

where J is the number of the day in the year (Julian day).

Terrestrial Radiation

Long-wave radiation emitted by the earth is termed as terrestrial radiation.

Total Radiation or Global Radiation

It is the sum of the beam radiation and diffuse radiation. i.e.,
Total or global radiation = Beam radiation + Diffuse radiation

Net Radiation

It is the difference between the sum of incoming radiation and the sum of out going radiation. The main factors affecting radiation balance are solar radiation (external factor), atmospheric composition, land use change, human activities, etc. (internal factors).

Net radiation (R_n) = total radiation in − total radiation out
= net shortwave radiation + net longwave radiation
= $(K\downarrow - K\uparrow) + (L\downarrow - L\uparrow)$
= [(beam radiation + diffuse radiation) − outgoing shortwave radiation]
+ [incoming longwave radiation − outgoing longwave radiation]

$$= [(S + D) - (S + D) \times a] + (L\downarrow - L\uparrow)$$

$$= (1 - a)\, R_s + R_{nl}, \tag{3.16}$$

where S is the beam radiation, D is the diffuse radiation, a is the albedo, L is the long-wave radiation, $R_s = (S + D)$, is the incoming short-wave radiation; and $R_{nl} = (L\downarrow - L\uparrow)$, is the net long-wave radiation.

3.6.2.3 Solar Energy Balance

Balance of energy indicates how the available total solar energy is used in the earth and atmosphere. Energy balance equation can be expressed as (ignoring advective energy and trapped energy):

$$R_n = H + LE + G, \tag{3.17}$$

where R_n is the net radiation, H is the sensible heat flux (heat transferred from the surface to the atmosphere by turbulent motion and dry convection), LE is the latent heat flux (heat extracted from the surface during evaporation of water), and G is the ground (soil) heat flux.

The components of the above equation may be positive or negative. Positive LE value means that evaporation is taking place, while negative value indicates condensation. Positive H value indicates that energy is used to heat the air, and on the contrary, negative values indicate that air is cooling and losing energy. Similarly, positive G value indicates that energy is transferred to subsurface, while negative value indicates that energy is transferring to the surface.

Heat energy travels from high to low temperature. So if the soil surface is warm, the ground heat flux is pointed downward (into the underlying surface).

3.6.2.4 Measurement and Use of Solar Radiation

Measurement

Instruments are available for measuring both total radiation (named as Pyranometer) and sky or beam radiation (named as Pyrheliometer). Under these two categories, instruments with different brand names are available from different manufacturers. But the working principles are almost similar. A pyranometer (or pyrheliometer) produces voltage from the thermopile detectors (Fig. 3.11), which is a function of incident radiation. A mechanism is used to detect and record this output. It is necessary to integrate radiation data over time, which can be accomplished by means of planimetry or electronic integrator. Now-a-days, digital instrument is available to measure and store radiation data.

Fig. 3.11 Sketch of a typical Pyranometer

Solar radiation data are expressed in different ways: $KJ/m^2/day$, KW/m^2 (Kilowatt per square meter), $cal/cm^2/hr$. The relationships between different units are as follows:

$1\ W/m^2 = 1.433 \times 10^{-3}\ cal/cm^2/min$
$KJ/m^2/day = 2.388 \times 10^{-2}\ cal/cm^2/day$
$1\ J = 0.2388\ cal$
$1\ J = 9.52 \times 10^{-4}\ BTU$

Uses of Solar Radiation

Solar radiation affects many physiological processes, particularly photosynthesis. Most crop growth and productivity models require total incident solar radiation data because photosynthesis, the production of biomass, requires light energy. This is also needed for inputs in simulation models of ET, ecological systems, and climatic impact studies. Photo-synthetically-active radiation (PAR) is measured infrequently, but it can be derived from total direct plus sky radiation (herein called solar radiation or global radiation).

3.6.2.5 Indirect Estimation of Solar Radiation

Despite the importance and scope of use of solar radiation data, it is not routinely measured in most weather stations in developing countries, and even in developed countries. The past historical data (non-instrumented periods) is often needed for model study. In addition, in crop fields where only simple weather data such as temperature is available, it can be estimated if a relationship is established with the solar irradiance at a complete weather station. This leads the researchers to establish a relationship between solar radiation and other simple weather elements.

A number of techniques are available for estimating solar irradiance. These vary in sophistication from simple empirical formulations based on common weather or climate data to complex radiative transfer schemes that explicitly model the absorption and scattering of the solar beam as it passes through the atmosphere. These complex models are capable of accurate estimates of incoming solar irradiance. However, they tend to be too complex and data-intensive for operational use, or are limited by requirements for site specific data, which are unavailable outside of a few locations.

For locations where measured values are not available along temporal and/or spatial scales, it can be estimated using empirical models (e.g., Richardson model). Techniques of multiple linear regressions may also be used to develop model for site-specific forecasting of solar radiation.

Richardson Model

Richardson (1985) developed an empirical relation between global solar radiation and temperature:

$$R_g/R_a = a(T_{max} - T_{min})^b, \tag{3.18}$$

where R_g is the global radiation, R_a is the solar radiation above the earth's atmosphere (extra-terrestrial radiation) on the given day (MJ m^{-2}), T_{max} is the maximum temperature of the day (°C), T_{min} is the minimum temperature of the day (°C), and a and b are the coefficients. Values of the coefficients a and b derived for different locations are cited below (Table 3.1).

Angstrom Model

A relationship between measured monthly mean of global radiation (R_g) and extra-terrestrial radiation (R_a) was established by Angstrom (Angstrom 1924):

$$R_g = R_a(a + b)(n/N), \tag{3.19}$$

where n is the bright sunshine hour, N is the maximum possible sunshine hour *or* day length.

The typical graph showing relationship between R_g/R_a and n/N is depicted in Fig. 3.12. The values of the coefficient a and b derived for different locations are cited below (Table 3.2).

Regression Model

The use of regression analysis to estimate daily solar radiation at locations with climatic data is attractive because it preserves the integrity of the observed time series and maintains the observed inter-seasonal variations. Global solar radiation (R_g) is highly correlated with surface daily climatic variables, including bright sunshine duration (S), air temperature range (ΔT), and precipitation status. Regression equations based on these variables have a strong physical basis. Day-time warming is driven in part by R_g, via the influence of R_g on the sensible heat budget of the lower atmosphere. Solar radiation is highly correlated with S.

Hook and McClendon (1993) used precipitation, extraterrestrial radiation, pan evaporation, and temperature range in a multiple regression equation and found that these parameters accounted for 78% of the variation in R_g at one location in Georgia. Extraterrestrial radiation is a function of latitude and solar declination (Smith et al. 1992). The day-length (photo-period) is also a function of solar declination and latitude, and hence may be used as a factor instead of extraterrestrial radiation in regression analysis for simplicity.

Table 3.1 Coefficients of Richardson model at different locations

Location	Coefficient		Source ref.
	a	*b*	
Oklahoma city, USA	0.0602	0.885	Richardson (1985)
Tifton, GA, USA	0.0846	0.680	Hook and McClendon (1992)
Mymensingh, Bangladesh	0.0593	0.718	Ali et al. (2005a)

Table 3.2 Coefficients of Angstrom model at different locations

Location	Coefficient		Source
	a	*b*	
Tropic to polar region	0.23	0.48	Black et al. (1954)
USA	0.35	0.61	Fritz and MacDonald (1949)
Canada	0.35	0.68	Mateer (1955)
Pelotas, Brazil	0.35	0.46	Da Mota (1976)
Piracicaba, Brazil	0.26	0.51	Cervelline et al. (1969)
Dhaka, Bangladesh	0.18	0.39	Hossain (1985)

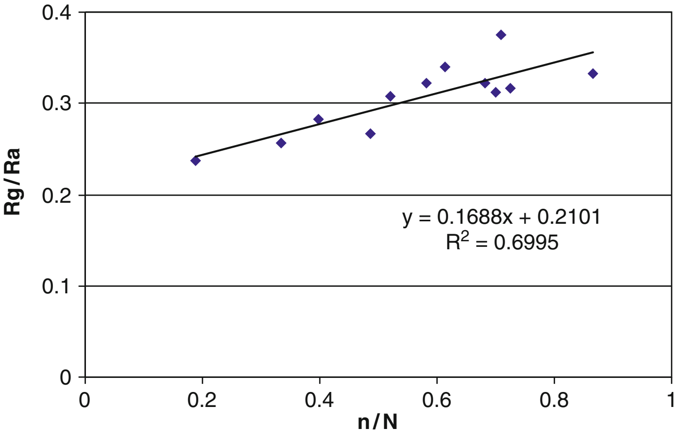

Fig. 3.12 Relationship between R_g/R_a and n/N

The general form of multiple regression model to estimate solar radiation from climatic variables is as follows:

$$R_g = a_0 + a_1x_1 + a_3x_2 + a_3x_3 + \dots\dots\dots + a_nx_n, \tag{3.20}$$

where R_g is the global radiation (MJ $m^{-2}d^{-1}$); $x_1, x_2, x_3, \dots\dots x_n$ are the climatic variables; and $a_0, a_1, a_2, a_3, \dots a_n$ are the regression coefficients.

Using maximum and minimum temperature, bright sunshine hour and day-length, the multiple regression developed for Mymensingh, Bangladesh (24°43′N, 90°26′E) is (Ali et al. 2005b):

$$R_g = -11.7075 + 0.1112\ T_{max} - 0.1388\ T_{min} + 0.5720\ n + 1.4251\ N, \quad (3.21)$$

where R_g (global radiation) is measured in MJ $m^{-2}d^{-1}$, T_{max} and T_{min} (maximum and minimum temperature) in °C, n (bright sunshine) and N (photo-period) in hour.

The coefficient values for each of the climatic variables are in accordance with the physical and/or theoretical basis. For example, the estimates of solar radiation is positively related with maximum temperature and negatively related with minimum temperature. Similarly, it is positively related with bright sunshine hour and photo-period.

3.6.2.6 Measurement of Bright Sunshine Period

The duration of bright sunshine at a place is measured by the instrument "Sunshine recorder." The sunshine recorder consists of a glass sphere mounted concentrically in a section of a spherical bowl (Fig. 3.13). Grooves are provided in the bowl to take cards. The focused sun's ray burn a trace on the card to indicate the period of bright sunshine during the day.

3.6.2.7 Calculation of Day-Length or Photo Period

The length of maximum possible sunshine duration (day-length) or photo-period in a day (N) can be obtained from the equation (Duffie and Beckman 1980):

$$N = (2/15)\cos^{-1}(-\tan\delta\tan\phi), \quad (3.22)$$

Fig. 3.13 View of a sunshine recorder (*Courtesy*: Raj Instruments)

where δ is the declination, φ is the latitude of the location concerned, positive to the north. The angles of the above equation are expressed in degrees. The unit of N is hour. The formula for determining δ is stated earlier.

Example 3.8 Estimate the extra-terrestrial radiation for a location having latitude of 23°N, for 15th June.

Solution We get,

$$R_a = 37.6 d_r(\omega_s \sin\psi \, \sin\delta + \cos\psi \, \cos\delta \, \sin\omega_s),$$

where, $d_r = 1 + 0.033 \cos(2\pi/365)J$.

Here, $J = 166$

Thus, $d_r = 1.03$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365}J - 1.39\right) = 0.4068(\text{rad})$$

$$\omega_s = \text{arc cos}\,(-\tan\varphi \tan\delta)$$

Here, $\phi = 23$ deg $= 0.40$ rad

Thus, $\omega_s = 1.75$ (all the angles are in radian)

Putting the input values in the above equation, we obtain $R_a = 42.8$ MJ/m^2/d (*Ans.*)

Example 3.9 Estimate the global radiation at Melbourne, Victoria (Australia) for 1 Nov 2008, from the following information:

$$\text{Latitude of } 36^\circ 15' \text{ S}, T_{\max} = 21.3^\circ\text{C}, T_{\min} = 12^\circ\text{C}, \text{bright sun shine hr} = 6.5$$

Solution Following the procedure of example 1, we get $R_a = 40.36$ MJ/m^2/d

We can solve the problem following Richardson or Angstrom model.

(a) From the Richardson model, we have:

$$R_g/R_a = a(T_{\max} - T_{\min})^b$$

Here, $R_a = 40.36$ MJ/m^2/d

$$T_{\max} = 21.3^\circ\text{C}$$

$$T_{\min} = 12^\circ\text{C}$$

Assuming $a = 0.068$, $b = 0.76$ (average value), We get $R_g = 14.94$ MJ m^{-2}d^{-1} (*Ans.*)

(b) From Angstrom model, we get, $R_g = R_a\,(a + b\,n/N)$

we get, $R_a = 40.36$ MJ/m^2/d
here, $n = 6.5$ h
we know, day length,

$$N = (2/15)\cos^{-1}(-\tan\delta\ \tan\phi)$$

where φ is the latitude of the location (in degree) $= -36.25°$ (negative for south), $\delta =$ declination (in degree), $\delta^0 = 23.5$ Sin ((360 × (284 − n)/365), [$n =$ number of day of the year (=305)] $= -15.06$

Then, $N = 13.55$ h
Assuming $a = 0.25$, $b = 0.50$,

$$\begin{aligned} R_g &= 40.36\,(0.25 + 0.5 \times 6.5/13.55) \\ &= 19.77\ \mathrm{MJm^{-2}d^{-1}} \end{aligned}$$

3.6.3 *Air Temperature*

Temperature is the leading factor influencing variation of weather. Temperature is the measurement of heating or cooling state of a substance. The solar energy from the sun is the main source of heat for the earth atmosphere. The rate at which the heat is received at the earth and the surrounding atmosphere is important for meteorological processes and agricultural practices.

3.6.3.1 Causes of Temperature Variation

At any particular location on the earth, the rate at which the heat energy (in the form of solar radiation) is received depends on the following factors:

(a) Latitude (relative position on the earth) or geographic factor
(b) Season (or Julian day of the year) or time dependent variation
(c) Atmospheric reflectivity (cloudiness and other impurities)
(d) Earth surface reflectivity/specific heat capacity (i.e., type of the surface)

As the temperature depends on the radiative heat energy, the factors that are responsible for radiative heat variation are also responsible for temperature variation. Temperature has geographical (spatial) and time-dependent (seasonal and diurnal) variations.

Geographical Variation

Geographical variation of temperature is caused by the following:

- Latitude
- Land and water masses ratio and distribution
- Vegetation
- Altitude/orographic feature
- Type and characteristics of earth surface

Latitude

The intensity at which the solar radiation falls on a surface in the earth depends on the latitude. At the equator, the solar radiation falls vertically, having higher intensity. In contrast, toward the north and south poles, the solar radiation falls in an inclined manner, resulting in lower intensity.

Atmospheric Reflectivity

On a clear sky, most of the incoming radiation reaches to the earth surface, while in a cloudy or unclear sky (due to dust and other suspended matters) most of the solar radiation is absorbed or reflected back to the atmosphere.

Type and Characteristics of the Surface

The radiant heat-energy absorption by the earth surface depends on the characteristics and absorbing capacity of the surface. In moist soil and water surface, the heat is used to vaporize the water. In contrast, the dry soil and concrete surface get heated up rapidly. Thus, temperature in large cities is several degrees higher than the surrounding villages. The heat releasing characteristics of the surface influence the night temperature near the earth.

Vegetation

Vegetative parts of the plants evaporate/transpire water to the atmosphere. To evaporate 1 gm of water, about 537 cal heat is absorbed. Thus, the plant acts as a heat absorber, which results in lowering of surrounding temperature. The annual maximum or mean temperature of a forest is about 1–3°C lower than the normal open area. The difference is highest during summer and minimum during winter.

Altitude

Air temperature usually decreases with elevation. Thus a station at mountain will exhibit lower temperature than the station at down the mountain. At night, the temperature at valley may be lower due to flow of cold air by gravity.

Temporal/Time-Dependent Variation

Seasonal Variation

While moving along the orbit, the distance of the earth from the sun varies. The intensity of solar radiation then varies inversely with the square of the distance, thus the intensity depends on the distance from the sun, which in turn depends on the season or day of the year.

Diurnal Variation

The daily temperature generally lags behind the solar radiation. The temperature begins to rise after sunrise, reaches to its maximum after about ½ to 1 h as the sun reached its highest altitude, and then begins to decrease to its minimum at about sunrise (Fig. 3.14).

Earth Surface Reflectivity

Reflectivity and specific heat capacity of land and water surfaces are not similar. In addition, sand and clay soil surfaces are different in the above properties. Thus, the

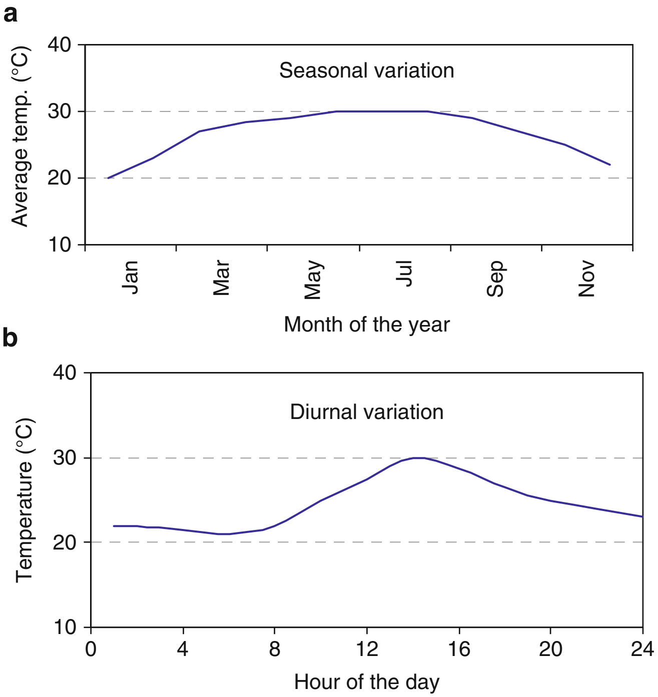

Fig. 3.14 Seasonal and diurnal pattern of temperature (example from 24°N, 89°S)

temperature varies accordingly. The sandy soil gets heated fast when compared to clayey soil because of their higher specific heat capacity, and cools faster as well. The water surface reflects much radiation and remains cooler than the land surface. As a result, the surface temperature varies according to the surface properties.

3.6.3.2 Heat Conduction and Temperature Profile

The heat received by the earth surface is transported through conduction and convection process. The air in contact with the earth's surface is heated by conduction. The next upper air-mass is heated consequently. Sometimes the air turbulence and wind flow transfer the heat (convection) vertically and horizontally.

As the volume of air mass increases by square of the distance from the earth surface, air temperature decreases with the increase in elevation. The rate of decrease in temperature with the increase in height is termed as lapse rate of temperature. Typically, air temperature decreases about 0.8°C per 100 m of elevation.

3.6.3.3 Measuring Temperature

Temperature is measured by using a "thermometer." It is very important to set up the thermometer at the right place to measure the temperature accurately. It should be set up in such a place that air can move freely, and sunshine or rainfall can not fall on it directly. Normally, it is placed on a shed or a wooden box where air can move freely.

For measuring the maximum and minimum temperature, a special type of thermometer "maximum and minimum thermometer" is used. Now-a-days, digital thermometer, having temperature sensor, is available.

Record of temperature is taken hourly, with several hours interval or once in a day, depending on the importance and intended use of the data. Temperature is expressed in different units. The relationship among different units is:

$$\frac{C}{5} = \frac{F - 32}{9} = \frac{R}{4}, \tag{3.23}$$

where C is the temperature in Celsius scale (°C), F is the temperature in Farenheight scale (°F), and R is the temperature in Romar scale (°R).

3.6.3.4 Expression and Interpretation of Temperature

Temperature can be expressed in different forms. These are as follows:

Average Temperature

Average temperature may be of daily, monthly, or yearly average:

Daily average. Accurate estimate of daily average temperature is the average of hourly temperature values. However, 3 or 6-h interval readings can give reliable estimates. In some instances, daily average is computed by the average of daily maximum and minimum temperature. There may be some bias in this case.

Monthly average. It is the average of daily maximum and minimum temperature of the month.

Yearly average temperature. It is the average of average monthly maximum and minimum temperature of the year.

Normal Daily Temperature

It is the average temperature of a particular day of the year, computed from the record of a long period (preferably $\geq$ 30 years).

Daily Temperature Range

It is the difference of maximum and minimum temperature of a particular day.

3.6.4 Humidity

3.6.4.1 Concept and Expression

Humidity is expressed in several forms. In general, it indicates the moisture in the atmosphere. The most commonly used expressions are absolute humidity, relative humidity, specific humidity, precipitable water, etc.

Absolute Humidity

It is the amount of water vapor present in a unit volume of air.

Relative Humidity

Relative humidity is the percentage ratio of the amount of moisture in a given volume or space, to the amount the space could contained at saturation. It is also expressed as the percentage ratio of actual to saturated vapor pressure.

Specific Humidity

It is the weight of water vapor (moisture) present in a unit weight of air. It is generally expressed as mg/Kg.

Precipitable Water

Total amount of water vapor present in a layer of atmosphere (or total atmosphere) is sometimes expressed in depth of equivalent water, termed as "precipitable water".

3.6.4.2 Measurement of Humidity

Generally, the instrument used for measuring humidity is called "Psychrometer." Other instruments are "Hair hygrometer" and "Dew-point hygrometer."

Psychrometer consists of two thermometers. One of the bulbs of the psychrometers is wrapped with fine wetted cloth. Because of evaporation (and resultant cooling), the reading of the wetted bulb is lower than that of the dry bulb. This difference is termed as "wet bulb depression." Then from appropriate psychrometric table, the value of humidity, dew point, and vapor pressure is obtained. With dew-point hydrometer, the dew point is measured directly.

Sources of Error in Measurement

Errors may be associated with insufficient ventilation, dirty cloth, and impure water. In using psychrometer, two thermometer readings are taken, thus having the chance of double error. Besides, in low temperature, a minor error in the reading can lead to a major error in the result. There may also be a chance that the wet-bulb reading is not taken when the wet-bulb thermometer is at its lowest temperature.

3.6.4.3 Variability of Humidity

Temporal Variability

Absolute and relative humidity vary with the season or month of the year, and diurnally (Fig. 3.15). Generally, the annual variation of absolute humidity (atmospheric moisture content) follows the pattern of temperature variation. But this is not true for relative humidity. Moreover, the relative humidity is greater in winter (despite of low absolute humidity) because of low temperature and consequently

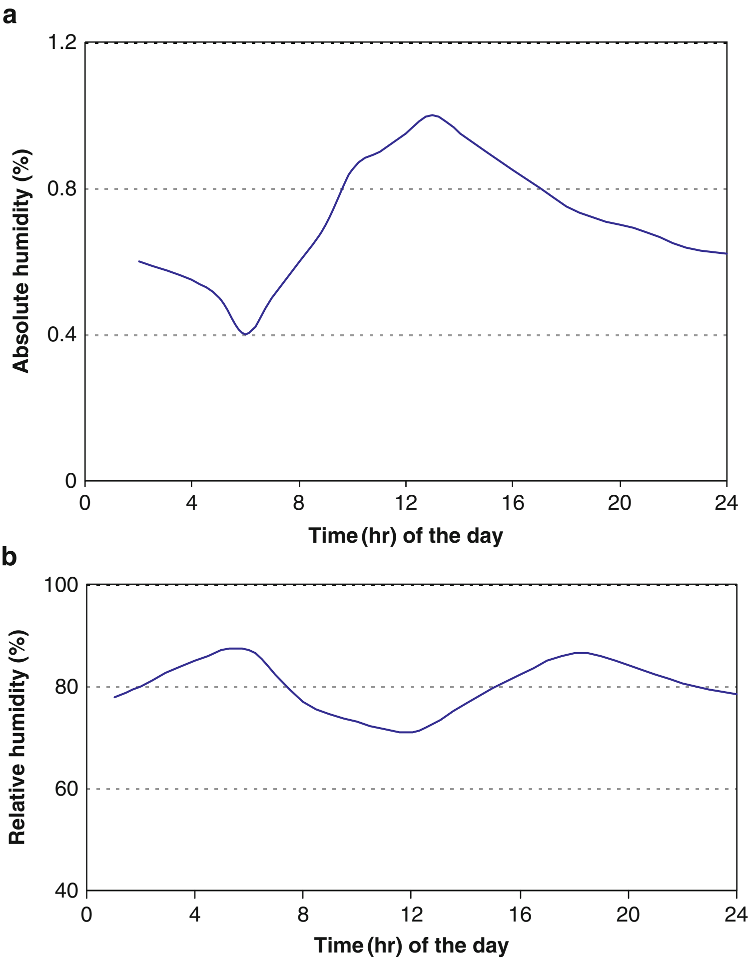

Fig. 3.15 Diurnal variation of (**a**) absolute humidity and (**b**) relative humidity

low saturation vapor pressure. Similarly, the relative humidity may be lower at summer, although the absolute humidity is higher.

Diurnally, the absolute and relative humidity vary with temperature pattern of the day. Mostly, they are in reverse trend (i.e., opposite in direction). In the early morning, the temperature is at minimum and the absolute humidity is also at minimum. The temperature rises rapidly to a maximum sometime at late-noon and then decreases gradually. Because of the increase in temperature toward noon, more water is evaporated from different sources (causing increase in absolute humidity). In addition, the water (vapor) holding capacity of the air increases with the increase in temperature (causing decrease in relative humidity).

Spatial Variability

The humidity varies with physiographic location, the latitude. Generally, the atmospheric moisture (i.e., absolute humidity) decreases with the increase in latitude. The relative humidity, opposite function of temperature, tends to increase with the increase in latitude. However, humidity is also influenced by other factors such as vegetation, land and water-mass ratio, orographic barrier, etc. Plants and vegetations add moisture to the atmosphere by transpiration. Large water bodies offer higher evaporation than do the land.

3.6.5 Air Pressure

3.6.5.1 Definition

Air pressure is the pressure exerted on a surface by the weight of air column over the surface. Atmospheric pressure is thus the pressure exerted by the atmospheric gases on the earth surface. It is expressed as force per unit area.

3.6.5.2 Measurement and Expression

Barometers are used to measure the air pressure at a particular location. It is expressed as millibars (mb), height of mercury (cm mercury), kg/cm^2, or Ibs/in^2. Earth atmosphere is pressing against each square inch with a force of 1 kg/cm^2(14.7 Ibs/in^2).

The line joining the points of equal pressure on the earth is termed as *isobar*.

3.6.5.3 Implication of Air Pressure Value

Low pressure in a location indicates stormy, cloudy climate, whereas high pressure indicates sunny and nice day.

3.6.6 Wind Speed

3.6.6.1 Concept and Expression

Wind can be regarded as air in motion. It has both magnitude and direction. Wind direction is that from which it blows. Wind speed is expressed as distance per unit time. Wind exerts considerable influence on evaporation, ET, and other hydrological and plant relevant processes.

3.6.6.2 Measurement

Wind speed is measured by an instrument called anemometer (Fig. 3.16). Different types of anemometer are available: three- or four-cup anemometer, vertical or horizontal axis anemometer, propeller type or pressure-tube anemometer.

3.6.6.3 Variation of Wind Speed

Wind speed varies with height from the ground. At the lower layer of atmosphere, wind speed is reduced due to friction of different obstacles such as tree, building, landscape, etc. This variation of wind speed with height is termed as wind profile. The lower layer is referred as friction layer. Above 500 m, the friction becomes negligible.

The variation of wind speed with height is usually expressed in logarithmic and power low profile. The power-low velocity profile is expressed as (Linsley 1975):

$$\frac{\bar{v}}{v} = \left(\frac{z}{z_1}\right)^k, \tag{3.24}$$

where $\bar{v}$ is the mean wind speed at some height z, v_1 is the mean wind speed at some height z_1, k is the coefficient, varies with surface roughness and atmospheric stability, and usually ranges from 0.1 to 0.6.

The logarithmic velocity profile is expressed as (Sutton1953):

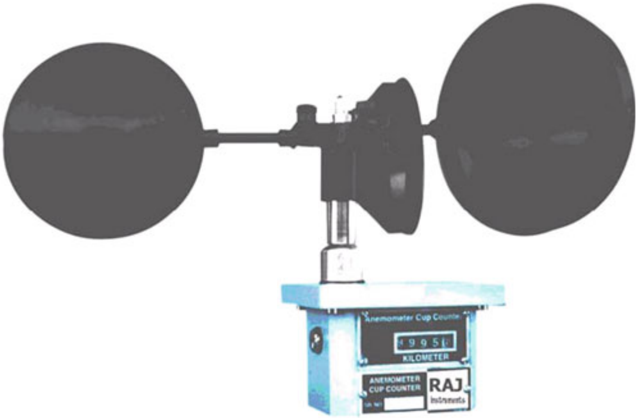

Fig. 3.16 View of an anemometer (*Courtesy*: Raj Instruments)

$$\frac{\bar{v}}{\bar{v}_1} = \frac{\ln(\frac{z}{z_0} + 1)}{\ln(\frac{z_1}{z_0} + 1)}, \tag{3.25}$$

where $\bar{v}_1$ is the measured velocity of wind at some standard height z_1, $\bar{v}$ is the mean velocity of wind at some height z, z_0 is the height up to which the wind speed becomes zero.

The z_0 is the measure of surface roughness. It varies with surface. For free water surface, its value is about 0.001–0.005 cm, and under crop condition it varies from 0.2 to 10. For forest, it may be from 60 to 300 cm.

Example 3.10 The air velocity at 2m height in a place was found 6 m/s and the roughness length was 0.8 cm. Find the velocity of air at 0.5m height in that place.

Solution We get from logarithmic velocity law,

$$\frac{\bar{v}}{\bar{v}_1} = \frac{\ln(\frac{z}{z_0} + 1)}{\ln(\frac{z_1}{z_0} + 1)},$$

Here, $z_1 = 2$ m, $v_1 = 6$ m/s
$z = 0.5$ m, $v = ?$
Assuming $z_0 = 0.8$ cm $= 0.008$ m
Putting the values in above equation, we get, $v = 4.51$ m/s (*Ans.*)

3.6.7 Evaporation

3.6.7.1 Concept and Factors Affecting Evaporation

Evaporation is not a weather variable, but it is a combined effect of weather variables. In most weather stations, open pan evaporation data are recorded.

The process by which liquid is transformed into vapor is called evaporation or vaporization. The physical process of evaporation is responsible for removal of water from plants, soil, and water bodies. Evaporation is the transfer of water molecules from water (or soil, plant) to the atmosphere. The rate at which water molecules leave the water surface is dependent on the temperature of water surface and the atmospheric pressure. Higher water temperature is synonymous with more vigorous molecular motion and thus result in more molecules leaving the water surface. Increase in atmospheric pressure inhibits the movements of molecules out of the water. As the evaporation takes place, the lower part of the atmosphere becomes saturated. If the water molecules in atmosphere are carried away by wind, continuous evaporation takes place. Considering this point, Dalton suggested a formula for calculating evaporation. Details regarding evaporation process, factors influencing evaporation (water and soil surface), and estimation of evaporation by empirical equations and by evaporation pan have been described in Chap. 7 (Field Water Balance).

Condensation

Condensation is the reverse process of evaporation. The process by which vapor is transformed into liquid form is called condensation. The partial pressure exerted by water vapor is termed as vapor pressure.

3.6.7.2 Latent Heats

Latent (i.e., hidden) heat is what happens during the phase change of water. Depending on the phase change, latent heat is either added to the water or released by the water into the environment during the phase change.

Latent Heat of Vaporization

Latent heat or hidden heat of vaporization is the amount of heat required to transform a unit mass of water to vapor without changing its temperature. The latent heat of vapor varies with temperature and can be calculated using the following equation (valid upto 40°C):

$$L_H = 597.3 - 0.564\,T, \tag{3.26}$$

where L_H is the latent heat of vaporization (cal/gm) and T is the temperature of water (°C).

From the above equation, we can find that, at zero degree C, the latent heat of vaporization is 597.3 cal/gm, and at 25°C, the latent heat of vaporization is 583.2 cal/gm.

Latent Heat of Condensation

Condensation is the reverse process of evaporation. The process by which vapor is transformed into liquid form is termed as condensation. Latent heat of condensation is the amount of heat released during transformation of a unit mass of vapors into water without changing its temperature. Since vaporization and condensation are reverse processes, the same amount of heat is released during the condensation process of water vapor to the water state.

Latent Heat of Fusion

Latent heat of fusion is the amount of heat released to convert unit mass of water into ice at the same temperature. The latent heat of fusion is taken as 79.7 cal/gm. The same quantity of heat is required for transforming 1 gm of ice to water at the same temperature.

Latent Heat of Sublimation

Latent heat of sublimation is the amount of heat required to convert unit mass of ice directly into vapor (without passing the intermediate liquid state) without changing temperature. Latent heat of sublimation is the sum of latent heat of fusion and latent heat of vaporization. For water at 0°C, its value is $(9597.3 + 79.7) = 677$ cal/gm.

3.6.8 Some Other Weather Phenomena

3.6.8.1 ENSO

The El Nino-Southern Oscillation (ENSO) phenomenon results from the two-way interaction between the ocean and atmosphere in the tropical Pacific Ocean. The ENSO involves two extreme phases:

1. Warm events, also known as "El-Nino" years
2. Cold events, also known as "La Nina"

Those years, which do not fall in these extreme phases, are labeled as "Neutral."

The southern oscillation index (SOI) is computed using the monthly fluctuations in the air pressure difference between Tahiti (representing eastern Pacific) and Darwin (representing western Pacific). On the one hand, when there is a significant negative value of SOI lasting for at least 6 months, we have an El-Nino condition. The more negative the index, the more intense the El-Nino. On the other hand, high positive values of the SOI indicate a La-Nina. A strong El-Nino/La-Nina usually corresponds to the persistent SOI of 1.5 (negative for El-Nino and positive for La-Nina), and above while the moderate one fluctuates between 0.8 and 1.5. A weak El Nino hovers between 0.4 and 0.8 of the SOI values. The time for successive El Nino and La Nina events is irregular, but they typically tend to recur every 3–7 years, lasting 12–18 months once they developed.

Another measure of ENSO phenomena is the SST, which is more often described in the form of its departure from the long-term average temperature (anomaly). Being important for monitoring and identifying El Nino and La Nina phenomena, several regions have been named in this context in the Tropical Pacific Ocean. The most common ones are Nino 1.2, Nino 3, Nino 3.4, and Nino 4. For a wide spread global climate variability, Nino 3.4 is generally preferred, because the SSTs variability in this region has been shown to have the strongest relationship with the shifting direction of rainfall pattern and this also greatly modifies the location of the heating that drives the majority of the global atmospheric circulation.

3.6.8.2 Tropical Cyclone

Tropical cyclones are violent whirling storms, several hundred of kilometers in diameter, which develop over tropical waters. Viewed from satellites high above the earth, a tropical cyclone appears as a powerful, tightly coiled system with spiral cloud bands emanating outwards. In a mature tropical cyclone, there exists a central region of relatively calm air and little cloudiness known as eye.

Tropical cyclones are classified as follows:

*Tropical depression.*This is an organized system of clouds and thunderstorms with a defined circulation and maximum sustained winds of 63 km/h (kmph) or less.

*Tropical storm.*This is an organized system of strong thunderstorm with a defined circulation and maximum sustained winds of 64–117 kmph.

*Typhoon.*This is an intense tropical weather system with a well-defined circulation and maximum sustained winds of 118 kmph or higher.

Tropical cyclones are formed over oceanic regions where the SST is 26°C or higher. In the Asian region, tropical cyclones, usually referred as to typhoons, are common during the Northern Hemisphere summer when the temperature over the Pacific Ocean is warm and favorable for convective activity. In the warm tropical ocean, low pressure systems are formed, move westwards, and develop from tropical depressions into storms and finally evolve into mature typhoons.

3.6.8.3 Thunderstorm

Thunderstorm is defined by the World Meteorological Organization as one or more sudden electrical discharges, manifested by a flash of lightening and a sharp or rumbling sound (thunder). A thunderstorm usually develops in an unstable and moist atmosphere. It grows laterally and vertically into a large dense cloud called cumulonimbus, with strong turbulence within the cloud and strong outflow below the base of the cloud. Thunderstorms are capable of producing hail, heavy rain, frequent lightening, and strong gusty winds. Some of the most severe weather occurs when a cluster of thunderstorms affect an area for a prolonged period of time.

Table 3.3 Weather parameters and their measuring instruments

Parameter	Measuring instruments
Air temperature	Thermometer, temperature sensor
Maximum and minimum temperature	Thermometer (special type)
Air pressure	Pressure gauge, absolute pressure sensor
Relative humidity	Hygrometer, humidity sensor
Wind speed	Cup anemometer
Wind direction	Wind vane
Solar radiation	Solarimeter, pyranometer, net radiometer, radiation sensor
Soil temperature	Thermometer, temperature sensor
Dew point	Dew point hygrometer

3.7 Instrumentation for a Weather Station

The essential parameters that should be measured in a weather station are air temperature, air pressure, relative humidity, wind speed, wind direction, solar radiation, soil temperature, dew point. The instruments for measuring such parameters are given in Table 3.3.

Now-a-days, multiple parameters can be measured with a single instrument, and the outputs are in digital form. Such weather stations are sometime referred to as *digital weather station*. Weather parameters are also measured with weather balloons or satellites.

3.8 Weather Forecasting and Agricultural Decision Making

3.8.1 Weather Forecasting

Man has hardly any control over weather. Despite major advances in modern agriculture, farming remains vulnerable to vagaries of weather. The success or failure of agricultural enterprises largely depends on weather. To take the advantage of favorable weather, or to minimize the impact of unfavorable weather on agriculture and to eliminate the climatic risk in agriculture, a reliable system of weather forecasting is needed.

3.8.1.1 Meaning of Weather Forecast

Meteorological observations taken throughout the world include data from surface stations, radar, aircraft, meteorological satellites, ships at sea, radiosondes. Weather forecasting is the prediction of weather that will be observed at a future time (i.e., what the weather will be like in an hour, tomorrow, or next week).

3.8.1.2 Methods of Forecasting

Weather forecasting process involves the following steps:

- Observation and analysis
- Extrapolation to find future state of atmosphere
- Prediction of a particular weather variable

For forecasting, the first requisite is the observed data. Data access policy varies among countries, but many of the data are transmitted on the Global Telecommunications System (GTS) of the World Meteorological Organization (WMO) to regional and global centers.

Forecast can be done few hours to several months ahead. Based on the time-range, the forecasts can be grouped as short-range, medium-range, and long-range forecast.

Short-range forecast: It is valid for several hours to 2 days
Medium-range forecast: It is valid for 3–7 days
Long-range forecast: It is valid for 7 days to 3 months

The accuracy of the forecast decreases with the increase in time-range of forecast.

There are several different methods that can be used for forecasting:

1. Persistence method (method of similarity)
2. Trend method
3. Climatological average method
4. Analog method
5. Statistical method
6. Numerical method

3.8.1.3 Factors Affecting Choice of a Forecast Method

The method or tool that the forecaster can use for forecasting depends on the following:

- Availability of data (parameters, number of data stations, frequency of data)
- Availability of software and hardware
- The experience of the forecaster
- Intended time-range of forecast (short-term or long-term)
- Degree of accuracy (or confidence) needed in the forecast

Description of Different Methods

Persistence Method (Method of Similarity)

Persistence method assumes that the conditions at the time of forecast will remain constant. For example, if it is a rainy day and temperature is 20°C, the persistence method predicts that it will be rainy and the temperature will be 20°C tomorrow. Persistence method performs well when the weather pattern changes little from day to day, and features on the weather map move very slowly. This method would work only for short-term forecasts.

Trend Method

The trend method uses the information of speed and direction of movement of fronts, area of cloud and precipitation, high and low pressure centers. Using the information, the forecaster can predict those features to be at some future time. For example, a cyclonic storm is traced 300 km from the sea shore having 200 km/h circular velocity and 50 km/h linear velocity, and the storm is moving toward the shore. Then using the trend method, one can predict that the storm will hit the shore after 6 h (300/50 = 6).

Climatological Average Method

The climatological average method involves averaging the target weather data accumulated over long period. For example, if it is required to forecast the rainfall amount for a location using climatological method on July 10, then it should go through all the rainfall data recorded for July 10 and take an average.

It is a simple way of producing a forecast. This method works well if the weather pattern is similar for the chosen time period of year. If the pattern is unusual (not stable, within transition zone) for the given time of year, this method often fails.

Analog Method

This method considers present weather scenario and considers a day in the past when the weather condition looked very similar (an analogy). Considering the both, the forecaster would predict that the weather in this forecast will behave the same as it did in the past. It is relatively complicated method of producing a forecast than the persistent, trend and climatology method.

For example, today is very hot and a dark cloud front is approaching to our area. Remembering similar weather conditions in the past, a hot day with dark cloud front approaching, that day, a heavy thunderstorm was developed in the afternoon. Using the analog method, the forecast will be that this dark cloud front today will also produce thunderstorm in the afternoon.

The analog method is difficult to use because it is nearly impossible to have a perfect analogy. Small differences between the present condition and the analogy (past) can lead to different outcome.

Statistical Method

Statistical forecasting systems based on the SOI or SST patterns remain the major source of seasonal forecasts used in agricultural practice.

Numerical Method

In this method, weather phenomena are forecasted by solving the equations (partial differential equations) that govern the behavior of the atmosphere. As these equations are nonlinear, exact solutions are impossible. Therefore, numerical methods obtain approximate solutions. Numerous numerical models have been developed so far. Different models use different solution methods (finite element, finite difference, spectral). Now-a-days, the meteorologists rely on numerical models to forecast the state of atmosphere into the future. The models have varying levels of approximation to the equations. Generally, the more exact the approximation, the more expensive the model is to use because more computer time is required to do the work.

Decreasing accuracy of numerical forecasts with increasing time-range (long-term forecast) reflects imperfections in theoretical processes of current numerical models.

Discussion

Understanding of the fundamental ENSO drivers coupled with easily measurable ocean and climate variables that index the overall state of the ENSO system have prompted the development of statistical systems that are now operationally used in many parts of the world. In dynamic forecasting, physically based models of atmospheric response to SSTs and possibly other predictor variables reflecting the state of the earth's surface is used.

Growing understanding of ocean–atmosphere interactions, advances in modeling the ocean–atmosphere system, and substantial investment in monitoring the tropical oceans now provide a degree of predictability of climate fluctuations several months in advance in particular seasons in many parts of the world. Timely, skillful climate forecasts offer the potential to reduce human venerability to agricultural impacts of climate variability through improved decision making, to either prepare for expected adverse conditions or take advantage of expected favorable conditions.

3.8.2 Application of Weather Forecasting in Agricultural Decision Making

Many critical agricultural decisions that interact with weather conditions must be made several months before impacts of weather materialized to exploit the benefit from forecast (either prepare for expected adverse conditions or to take advantages of favorable condition). The following are the prerequisites for effective use of climate forecasts:

1. Forecast of relevant components of climate variability in relevant periods, at an appropriate scale, with sufficient accuracy and lead time for relevant decisions.
2. Effective communication of relevant information.
3. There should be existence of decision options that are sensitive to the incremental information that forecasts provide, and compatible with decision maker's goals and constraints.
4. There should be institutional commitment and favorable policies.

3.8.2.1 Application of Weather Forecast

The major fields of applications of weather forecast are as follows:

- Determination of appropriate time for sowing or harvesting of crop.
- Based on weather forecasts, producers may adjust their inputs.
- Estimation of irrigation or drainage need (or other cultural operation) and preparedness for that.
- Preparedness for any hazardous weather phenomena.
- Analysis in exploring decision options and their risks.
- Use of seasonal forecasts in commodity forecasting for government policy support and for decision making in industry.
- Development of trade policies based on commodity forecast.

3.8.3 Copying Strategy for Hazardous Weather Phenomena

Copying strategies for weather phenomenon may be broadly classified as:

(1) Preparedness
(2) Mitigation practices

Preparedness as a coping strategy means preparedness for what cannot be prevented. Mitigation practices as a coping strategy means preparedness for what can be prevented. Avoiding hazardous weather phenomena through monitoring and early warnings (forecast/identify disasters and their probability, evolve signal/warning mechanisms), production adaptation strategy, preparation for agricultural rehabilitation program after the flood, flood hazard mapping for land-use planning, etc. are the strategies of preparedness. Crop contingency plan depends on extent of damage to standing crop and time of season. Flood water detention, flood diversion attempts for agricultural purposes, etc. are the strategies of mitigating effect of high intensity rainfall (flood). In case of heat and cold waves, the changes in crop, growing periods, planting dates, varieties, irrigation and fertilizers, intercropping, growing off-season crops, and choosing resistant varieties (together with microclimate management and agronomic manipulation) are the farm level mitigation. For tropical storms, plantation of tree (implementation of afforestation), creating shelterbelt, and selection of crop cultivar having strength to stand against strong wind, drilling depth, sowing date, seed rate etc. are the farm level mitigation practices. For heat wave, using seasonal temperature forecasting, preparedness such as shifting planting date, changing variety, or the both, to ensure that the temperature sensitive stage (e.g., flowering in case of cereal) can be avoided, or tolerated to a certain degree.

From historic time, farmers have developed a wide range of management practices to cope with weather variability (for adapting their farming systems), which include premonsoon dry-seeding, stubble mulching, and intercropping. In many regions of the world, agricultural decision makers are incorporating climate forecasts into their decisions. For example, potato farmers in Florida saved their 1997 winter crop by contouring their fields and clearing state-owned drainage canal in anticipation of excess rain associated with El Nino. An Africa-wide agricultural input supplier markets seeds of cultivars based on their appropriateness to seasonal rainfall forecasts, and uses forecasts in planning their distribution among regions. Periodic regional climate outlook forums in Africa and Latin America bring forecast providers and stackholders together regularly to develop consensus forecasts and explore opportunities for their use. Agricultural support institutions in Australia, Zimbabwe, and the southeast USA have incorporated seasonal climate forecasts into their operational programs for advising farmers.

3.8.3.1 Challenges

Although weather events always been an integral part of human existence, our collective coping strategies have so far been limited by the complexity of systems responses to climate, environment and management, and our ability to predict such systems dynamics. Climatic phenomena or climate variability relevant to agricultural management occurs at a range of frequencies or time scales, ranging from intra-seasonal, inter-seasonal, decadal, multi-decadal. The major challenge in coping with climatic phenomena is to further increase our understanding of causes and consequences of climate phenomena and climate variability. Understanding the interactions between climate and agro-ecosystems, and the nature and timing of relevant climate-sensitive decisions, can clarify what forecast information is most relevant to the decision problem in a particular context.

Challenges and complexities may arise from prediction process and also from alternating decision option process. Hasselman (2002) noted two factors that impose limits on predictability of future climate state:

(1) Uncertainty in initial conditions, including uncertainties about boundary conditions
(2) Errors associated with, and gaps in, observational measurements and limitations of climate models, including the parameterization of physical process. The complexity of agro-ecosystem response to the range of combinations of management, initial soil conditions, climatic outcomes, and market outcomes – the “curse of dimensionality” – presents difficult methodological challenges for predicting impacts of decision options.

A major challenge to estimate the effects of improved climate forecasts on commodity supply is incorporating forecast information into price expectations.

Although the use of climate prediction is analogous in many respect to other agricultural technology, its dynamic nature and potential interaction with a range of agricultural decisions present particular challenges to management capability. Climatic forecast, choosing alternate decision option (based on possible outcome) and relevant policy issues, is a problem of multi-faceted, multi-dimensional and cross-disciplinary nature, and the challenge remains to actually integrate those components into management practices or policy frameworks.

3.9 Agro-Climatic Indices

3.9.1 Use of Climatic Indices and Heat Units

Crop development is generally dependent on thermal index or heat units. Different thermal and photo-thermal indices are used in crop growth interpretations. Thermal indices predict and describe development rate more accurately than time in days, and are commonly used to rate cereals for maturity. Maderski et al. (1973) reported that the coefficient of variation was small and half in describing the timing of physiological development of corn based on accumulated heat units, when compared with the calendar-day method. Growing-degree-days have also been used to develop physiological clocks for sorghum, alfalfa, cotton, and soybean.

An ideal index would estimate a constant number of heat units for a given genotype to reach a specific development stage. Phenology is an essential component of the crop-weather models, which can be used to specify the appropriate time and rate of specific phasic development processes. The thermal and heliothermal requirement of any crop or variety are specific for maximum yield.

3.9.2 Different Indices and Their Description

The most common agro-climatic indices are degree-days, crop heat units, heliothermal units, and photo-thermal units.

3.9.2.1 Degree-Days or Growing-Degree-Days (GDD)

Cumulative thermal time (degree-days, above a threshold temperature) is derived from the temperature. Growing-degree-day (GDD) is widely used for describing the temperature responses to growth and development of crops. GDDs required to

Crop	Base temperature
Rice	15°C
Wheat	5°C
Mungbean	10°C
Corn	5°C
Mustard	8°C

reach maturity (or to reach a particular phase) are calculated following Nuttonson (1995):

$$\mathrm{GDD} = \sum_{i=m}^{n} (T_\mathrm{A} - T_\mathrm{B})\Delta t, \tag{3.27}$$

where T_A is the average of daily maximum (T_max) and minimum (T_min) air temperature, T_B is a base temperature below which development is assumed to cease, m is date of sowing, n is date of physiological maturity, and Δt is a time step in days.

The base temperature is the minimum threshold temperature below which the growth is apparently or assumed to be ceased. The base temperature for different crops is given below:

A physiological clock can be developed based on GDDs.

3.9.2.2 Crop Heat Unit

Crop heat unit (CHU) for cereals may be calculated by the formula given by Cutforth and Shaykewich (1990):

$$\mathrm{CHU} = \sum (X + Y)/2, \tag{3.28}$$

where $X = 1.8\ (T_\mathrm{min} - 5)$, for $T_\mathrm{min} \geq 5°\mathrm{C}$
$= 0$, for $T_\mathrm{min} < 5°\mathrm{C}$
$Y = 3.33\ (T_\mathrm{max} - 10) - 0.083(T_\mathrm{max} - 10)^2$, for $T_\mathrm{max} \geq 10°\mathrm{C}$
$= 0$, for $T_\mathrm{max} < 10°\mathrm{C}$

3.9.2.3 Heliothermal Unit

Heliothermal unit (HTU) is calculated by multiplying degree-days with daily actual sunshine hours:

$$\mathrm{HTU} = \sum \mathrm{GDD}.SH = \sum_{i=1}^{n} (T_\mathrm{A} - T_\mathrm{B})\Delta t.SH, \tag{3.29}$$

where *SH* is the daily actual sunshine hour.

3.9.2.4 Photo-Thermal Unit

Photo-thermal units (PTU) is the product of GDD and corresponding day length for that day. On daily basis,

$$\mathrm{PTU} = \mathrm{GDD} \times (\text{day length}). \tag{3.30}$$

For a particular period or whole growing period,

$$\sum \mathrm{PTU} = \sum \mathrm{GDD} \times (\text{day length}),$$

where “day length” refers to maximum possible sunshine hours.

3.9.2.5 Heat-Use Efficiency

Day no.	Maximum temp (°C)	Minimum temp (°C)
1	36.5	24
2	35	25
3	37	27
4	35	25
5	36.5	26
6	35.5	25
7	34	23

Heat-use efficiency (HUE) for seed *or* total dry matter is calculated as:

$$\mathrm{HUE} = Y/\mathrm{AHU}, \tag{3.31}$$

where Y is the Seed yield or total dry matter (Kg/ha), AHU is the accumulated heat units (degree-days), HUE is in kg/ha/degree-day.

Day no	T_{max}	T_{min}	T_{av}	Degree-day
1	36.5	24	30.25	15.25
2	35	25	30	15
3	37	27	32	17
4	35	25	30	15
5	36.5	26	31.25	16.25
6	35.5	25	30.25	15.25
7	34	23	28.5	13.5
		Total deg.-day, GDD=		*107.25*

3.9.3 Examples on Heat Unit Requirement of Crop

Example 3.11 Calculate the degree-days for rice crop for the following duration:

Day no.	T_{max}(°C)	T_{min}(°C)	Sunshine (h)	Day length (h)
1	25	20	6	10.0
2	26	20.5	6.5	10.1
3	25.5	21	6	10.2
4	26	21.5	7	10.3
5	27	22	7	10.4
6	27.1	22.5	8	10.5
7	27.5	23	7.5	10.6
8	27.9	23.5	9	10.7
9	28.3	24	8	10.8

Solution For rice, base temperature = 15°C
We know,

$$\mathrm{GDD} = \sum_{i=m}^{n} (T_\mathrm{A} - T_\mathrm{B})\Delta t,$$

where T_A is the average temperature, T_B is the base temperature, Δt is the time step = 1 day.

Thus, degree-days for the period =107.25 (*Ans.*)

Example 3.12 Find out the GDD, CHU, HTU, and PTU for wheat crop for the following days using the data given below:

Solution We know,

$$\mathrm{GDD} = \sum_{i=m}^{n} (T_\mathrm{A} - T_\mathrm{B})\Delta t. \tag{a}$$

Day no.	T_{max} (°C)	T_{min} (°C)	Sunshine (hr)	day length (hr)	GDD	CHU.			HTU	PTU
						X	Y	CHU		
1	25	20	6	10.0	17.5	27	31.3	29.1	105	175
2	26	20.5	6.5	10.1	18.25	27.9	32.0	30.0	118.63	184.3
3	25.5	21	6	10.2	18.25	28.8	31.7	30.2	109.5	186.2
4	26	21.5	7	10.3	18.75	29.7	32.0	30.9	131.25	193.1
5	27	22	7	10.4	19.5	30.6	32.6	31.6	136.5	202.8
6	27.1	22.5	8	10.5	19.8	31.5	32.7	32.1	158.4	207.9
7	27.5	23	7.5	10.6	20.25	32.4	32.9	32.6	151.88	214.7
8	27.9	23.5	9	10.7	20.7	33.3	33.0	33.2	186.3	221.5
9	28.3	24	8	10.8	21.15	34.2	33.1	33.7	169.2	228.4
10	28.7	24.5	9	10.9	21.6	35.1	33.2	34.2	194.4	235.4
Sum					195.8			317.5	1461.1	2049.3

$$\mathrm{CHU} = \sum (X + Y)/2 \tag{b}$$

where $X = 1.8\ (T_{\min} - 5)$, for $T_{\min} \geq 5°\mathrm{C}$
$= 0$, for $T_{\min} < 5°\mathrm{C}$
$Y = 3.33\ (T_{\max} - 10) - 0.083(T_{\max} - 10)^2$, for $T_{\max} \geq 10°\mathrm{C}$
$= 0$, for $T_{\max} < 10°\mathrm{C}$

$$\mathrm{HTU} = \sum \mathrm{GDD}.SH = \sum_{i=1}^{n} (T_\mathrm{A} - T_\mathrm{B})\Delta t.SH \tag{c}$$

$$\sum \mathrm{PTU} = \sum \mathrm{GDD} \times (\text{day length}) \tag{d}$$

The calculations are summarized in Table given below:

3.10 Climatic Potential Yield

3.10.1 Concept and Mathematical Formulation

Crop yield in a particular environment is an interaction of genotype × environment. The upper limit of crop production is set by the climatic conditions and the genetic potential of the crop. On the one hand, genetic potential of a cultivar can not be explored if the environmental condition does not permit that level. On the other hand, environmental potential can not be exploited unless the genetic potential reaches to the environmental potential. Chang (1981) demonstrated that crop response to fertilizer application is reduced in areas of low climatic yield potential.

Crop production in an area can be better described as (Ghuman and Singh 1993):

$$\mathrm{DM} + \mathrm{O_2} = f(\mathrm{R_g}, \mathrm{H_2O}, \mathrm{CO_2}, \mathrm{QP}, N, \mathrm{EM}), \tag{3.32}$$

where DM is the dry matter production, O_2 is the oxygen evolved, R_g is the incoming solar radiation (global radiation), H_2O is the water, CO_2 is the carbon

Plant type	Maximum photosynthetic efficiency (%)
Field crops	6.6
Algae	12

dioxide assimilated, QP is the quality *or* genetic potential of plant material, N is the essential nutrients for plant growth, and EM is the efficiency of management (control of weeds, pests and diseases).

If H_2O, QP, N, and EM are not limiting in the above equation, the potential dry-matter production is determined by solar radiation (R_g).

Dry matter production for a particular crop season can be calculated as:

$$\mathrm{DM} = \frac{R_g \times E_p}{C_d}, \tag{3.33}$$

Crop	Effective growing period (period of capturing solar radiation)	Solar radiation for the months (MJ/m^2/day)
Rice	June, 15–Oct, 30	12, 13, 11, 10, 9.0
Wheat	Nov, 15–Mar, 20	9, 10, 11, 12, 13

where DM is the dry-matter production (Mg/m^2-day), R_g is the available solar energy for the crop during its growth period (MJ/m^2-day), E_p is the photosynthetic efficiency (%), C_d is the energy needed to produce 1 gm dry-matter (MJ).

Photosynthetic efficiency (E_p) for different types of plants is given below (Mitsui et al. 1977):

Energy needed to produce 1 gm dry-matter of field crop is 4226 cal (0.01768 MJ).

Thus using the above equation, climatic potential yield for a particular region can be calculated.

3.10.2 Example on Calculation of Climatic Potential Yield

Example 3.13 Calculate the environmental potential yield of an area with the following information:

If the actual grain and straw yield production for rice are 7.0 and 10 t/ha, and for wheat 5 and 7 t/ha, respectively; find out the scope to increase dry-matter production.

Solution (a) Captured solar radiation for *Rice* during growing period = (15 × 12) + (31 × 13) + (31 × 11) + (30 × 10) + (31 × 9) = 1,503 MJ/m^2

Environmental potential yield (dry-matter yield) per hectare (=10^4m^2) during this period, DM = AE × E_p/C_d

Taking $E_p = 6.6\%$, $C_d = 0.01768$ MJ for 1 gm drymatter production, we obtain,

$DM = [1{,}503 \times (6.6/100)/0.01768] \times 10^4 = 56.107$ ton (or Mega gram, Mg)

Similarly, for *wheat*,

Captured solar radiation during growing period $= (15 \times 9) + (31 \times 10) + (31 \times 11) + (28 \times 12) + (20 \times 13) = 1{,}382\ \mathrm{MJ/m^2}$

$DM = [1{,}382 \times (6.6/100)/0.01768] \times 10^4 = 51.59$ Mg (ton)

Total potential drymatter production (during the two crop season) = 107.69 t/ha (*Ans.*)

(b) Total actual (existing) drymatter production = 29 t/ha, which is only 26.93% of the potential drymatter production. Hence, there is a scope to increase drymatter production in that area, by genetic improvement and improved cultural practices.

3.11 Agro-Climatic Classification for Crop Suitability

Depending on the agro-climatic suitability, the crop production may be increased or decreased. It is generally recognized that climatic classifications present only a

Table 3.4 Suitability class for agro-climatic evaluation of rice cultivation [after Sys (1985) with permission]

Climatic characteristics	Agroclimatic land class[a]				
	S1	S2	S3	N1	N2
Mean rainfall (mm) for rain-fed rice during growing season	>1,400	>1,000	>800	<800	<800
Mean temperature at crop development stage (°C)	24–36	18–42	10–45		any
Mean temperature at ripening stage (°C)	25–38	20–42	17–45		any
Mean minimum temp. at ripening stage (°C)	17–25	10–28	7–30		any
Average daily maximum temp., warmest month (°C)	30–40	26–45	21–50		any
Relative humidity at tillering (%)	55–90	any			
Relative humidity at vegetative stage (%)	50–90	any			
Relative humidity for rain-fed rice after milk stage (%)	40–90	>30	<30		
Relative humidity at harvest (%)	<60	<80	>80		
Ration of growing season bright sunshine hour to photo-period or day length (n/N)	>0.75	>0.45	<0.45		

[a] S1 = suitable land, S2 = moderately suitable, S3 = marginally suitable, N1 = actually unsuitable but potentially suitable, N2 = actually and potentially unsuitable

broad climatic pattern of the world. They are of limited value in agricultural land-use planning. Climatic types and the distribution of crops are not closely matched. Climatic types are largely determined by mean temperature, rainfall, and ET. Other elements important for agriculture such as solar radiation, photoperiod, night temperature, and wind velocity are ignored. Realizing the limitations of climatic classification, Nuttonson (1947) undertook a series of studies to define "climatic analogues" for rice, wheat, and other grain crops.

Agro-ecological zoning is a first step toward suitability estimation of crops for a particular area. Many countries have set up agro-climatic regions for the purpose of agricultural land-use planning and management. These are supposed to be uniform regions with similar climatic characteristics that readily permit the transfer of technology.

Studies of climatic analogues would be more useful for a crop whose ecological limits are relatively narrow (specifically if an attempt is made to determine the optimum climatic environment). Sys (1985) suggested suitability class for agro-climatic evaluation of rice cultivation (Table 3.4).

3.12 Greenhouse Effect and Its Consequences

3.12.1 Concept and Causes of Green House Effect

3.12.1.1 Green House Effect

The name "green house" was originated from the "glass house" used to grow plants, where heating of the glasshouse was accomplished by sunlight passing through sealed, transparent windows. In a glasshouse, visible radiation from the sun passes almost unimpeded through the glass and is absorbed by the plants and the soil inside. The thermal radiation that is emitted by the plants and soil is absorbed by the glass, which then re-emits some of it back into the green house. The glass thus acts as a "radiation blanket" helping to keep the green house warm. Without atmosphere surrounding the earth surface, the earth surface temperature would be very low (about −18°C). But the present temperature exists because of a layer of gases called *green house gases*, which affects the energy balance of the earth system by absorbing infra-red (long wave) radiation.

Under normal condition, energy from the sun passes through the atmosphere, some of which warms the surface of the earth and the rest is then reflected back into space. But certain gases (greenhouse gases) are now accumulating in the atmosphere and acting like the glass in a greenhouse, trapping this radiation, causing the earth surface to heat up even further. The term *green house effect* is widely used to describe the trapping of excess heat by the rising concentration of greenhouse gases in the atmosphere. The *green house effect* refers to circumstances where the short wavelengths of visible light from the sun pass through a transparent medium and are absorbed, but the longer wavelengths of the infrared reradiation from the heated objects are unable to pass through that medium. The trapping of the long wavelength radiation leads to more heating and a higher resultant temperature.

3.12.1.2 Greenhouse Gases and Process of Their Development

The atmosphere surrounding the earth is made up of nitrogen (78%), oxygen (21%), water vapor, and other various trace gases making up the remainder (1%). The trace gases comprise Carbon di-oxide, Hydrogen, Argon, Helium, Neon, Nitrous oxide, Ozone. These gases (including water vapor) are often called *green house gases*, because from the solar energy during the day, the earth received heat energy and these gases act like a *green-house trapping* in the heat. If these gases do not exist, the earth would freeze over during the night. The issue is the increase in greenhouse gases, which is trapping more heat, and causing a rise in global temperature.

The *green house gases* are the gases that effectively absorb and trap heat, and responsible for increasing atmospheric temperature. The greenhouse gases comprise less than 1% of the atmospheric gases. The major green house gases in the atmosphere are carbon di-oxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), sulphur dioxide (SO_2), fluorocarbons (hydro fluorocarbons, per fluorocarbons, chloro-fluorocarbons), sulphur hexafluoride (SF_6). The chloro-fluoro-carbons (CFCs), although exist in trace quantity, can have a large effect because of its higher warming potential. Hydro fluorocarbons, per fluorocarbons, and sulphur hexafluorides rarely occur in nature. These are man-made and emitted from refrigerator, aerosol spray, propellants, and cleaning solvents. Perfluorocarbons, one type of halocarbon, are produced during aluminium production.

The earth temperature only rises until the amount of infrared or long-wave radiation leaving the earth balances the amount of energy coming in from the sun. As long as the amount of greenhouse gases in the air stays the same, and as long as the amount of heat arriving from the sun is constant, equilibrium is established. In equilibrium, the natural greenhouse effect maintains the average temperature of the earth (at about 14–15°C). A small increase in greenhouse gases disrupts the heat equilibrium of the atmosphere. Before the industrial revolution (which was started in England about 210 years ago), the mix of gases that made up the atmosphere was relatively constant. The industrial processes release different greenhouse gases to the atmosphere. In addition, rapid increase in the world's population forced for more extensive and intensive agriculture, which produce more methane gas. Current analysis suggests that the combustion of fossil is a major contributor to the increase in the carbon dioxide. Mankind is burning fossil fuel (specifically coal) to drive steam engines for industry and to generate electricity. People are also using another fossil fuel, petroleum, for transport. When fossil fuels are burnt, carbon dioxide, methane, nitrous oxide are given off as gases. Now-a-days, people are using huge amount of petroleum. At the beginning of the twentieth century, annual global oil output was about 150 million

Table 3.5 Source, sink, and role of major greenhouse gases in the environment

Greenhouse gas	Source	Sink	Role/mode of action
Methane (CH_4)	Rice field	Microorganisms uptake from soil	Produce CO_2
	Biomass burning	Reaction with OH	Absorbs long-wave (infrared) radiation
	Digestive fermentation from cattle and other livestock		Affects tropospheric O_3 and OH
	Leaks from natural gas pipeline		Affects stratospheric O_3 and H_2O
	Landfill		
Carbon dioxide (CO_2)	Fossil fuel burning	plants (during photosynthesis)	Absorbs long-wave radiation
	Deforestation		
	Cement manufacture		
Ozone (O_3)	Photo-chemical reactions with O_2	Catalytic chemical reactions involving HO_x, NO_x species	Absorbs ultraviolet and long-wave radiation
Cholorofluorocarbons (CFCs)	Industrial output	Insignificant	Absorbs long-wave radiation
	Refrigerants		
	Foaming agents		Affects stratospheric O_3
	Propellants		
Sulphur dioxide (SO_2)	Biomass burning	Insignificant	
	Coal burning		
Carbon monoxide (CO)	Industrial output	Reactions with OH	Produce carbon dioxide
	Output from transport		Affects stratospheric O_3
Nitrous oxide (N_2O)	Agriculture	Insignificant	
	Biomass burning		
	Industrial processes		

Table 3.6 Relative warming potential of greenhouse gases [Adapted from IPCC (2001)]

Greenhouse gas		Estimated lifetime (Yrs)	Global warming potential[a]		
			20 years	100 years	500 years
Carbon dioxide (CO_2)		Variable	1	1	1
Methane (CH_4)		12	62	23	7
Nitrous oxide (N_2O)		114	275	296	156
Chlorofluorocarbons (CFCs)					
i.	$CFCl_3$ (CFC-11)	45	6300	4,600	1,600
ii.	CF_2Cl_2 (CFC-12)	100	10,200	10,600	5,200
iii.	$CClF_3$ (CFC-13)	640	10,000	14,000	16,300
iv.	$C_2F_3Cl_3$ (CFC-113)	85	6,100	6,000	2,700
v.	$C_2F_4Cl_2$ (CFC-114)	300	7,500	9,800	8,700
vi.	C_2F_5Cl (CFC-115)	1,700	4,900	7,200	9,900

[a] The estimation is based on the instantaneous injection of 1 Kg of each gas, relative to 1 Kg of CO_2

barrels of oil. Now, that amount is extracted globally in two days only. Burning this huge amount of fossil fuels (millions of tons) releases huge amount of carbon dioxide that are accumulating in the atmosphere. According to IPCC (2007), the primary sources of greenhouse gas emissions are the energy supply sector (26%), industry (19%), forestry (17%), agriculture (14%), transport (13%), residential and commercial building (8%), and waste water (3%) of total emissions. Source and sink of major greenhouse gases are summarized in Table 3.5.

3.12.1.3 Warming Potential of Green House Gases

IPCC (Intergovernmental Panel on Climate Change) introduced global warming potential of green house gases with respect to CO_2. The global warming potential refers to the relative strength of individual green house gases to warm the earth. It takes into account the differential abilities of various gases to absorb radiation and their atmospheric lifetimes. Different greenhouse gases pose different effect on trapping heat (Table 3.6). Despite their small concentrations, halocarbons have a significant greenhouse effect. Exact estimation of warming potential requires knowledge of the fate of the emitted gases and their radiative forcing. As a result, the global warming potential relative to CO_2 encompasses certain uncertainty.

3.12.1.4 Trends of the Greenhouse Gas Concentrations

The proportion of greenhouse gases has been increasing significantly since the industrial revolution. The rapid increase in human activities (industrialization, extensive agriculture, deforestation, use of refrigerator, aerosols, insecticides, pesticides, etc.) meant that more greenhouse gases were released into the atmosphere.

3.12.1.5 Cyclic Variation of Greenhouse Gases

There is interesting cyclic variation of (concentration of) greenhouse gases, especially of carbon dioxide. During the seasonal crop growing period, the concentration of carbon-dioxide decreases due to photosynthetic requirement of the vegetation and after that, the concentration regains its position. In the Northern Hemisphere, the carbon-dioxide concentration increases during fall and winter and declines during spring and summer. This cycle follows the growth and death of vegetation.

3.12.2 Possible Consequences of the Greenhouse Gases

The greenhouse gases those emitted as a result of industrial activities from the industrialized countries never remain under the sky of the same countries as these gases cross across the border. So throughout the world, all countries are suffering

Table 3.7 Contribution of greenhouse gases to climate change in 1990 (IPCC 1992)

Gas	Emissions	Concentration (ppm[a])	Annual increase in concentration (%)	Contribution (%)
CO_2	26,000	354	0.5	50
CH_4	300	1.72	0.9	23
NO_2	6	0.31	4	2
CFCs and HCFCs	1	0.001	0.25	23

[a] Parts per million in atmosphere

with the bad impact of greenhouse effect and the consequent bad impact of weather is manifested with recent increase in frequency and intensity of tornado, flood, drought, etc.

Increase in greenhouse gases may result in global warming (increase in temperature). Contribution of greenhouse gases to climate change is shown in Table 3.7. An increase in earth temperature would bring changes to the weather of the entire globe. This makes it an international issue. The scientists strongly agree that the levels of greenhouse gases are rising, but there is less certainty what the precise effects of this will be (how much warmer of the globe or how quickly it will happen). Mathematical models are being used to understand these effects. These models take into account many processes that together determine the behavior of the atmosphere. The possible long-term consequences may be the following:

- Increase in surface air temperature
- Melting of the polar ice caps and a rise in sea level
- Generate rehabilitation problem in some parts of the world
- Increase or decrease in precipitation
- Shifting of crop season
- Alteration of crop rotation

3.12.3 Remediation/Abatement of Greenhouse Gas Generation

Each individual country is responsible for their own green gas production. The power generating sources such as solar power have no fuel burning, hydro power plants have no carbon effects, and windmill power plants have no carbon effects.

In the 1980s, the World Meteorological Organization and the United Nations Environmental Program established an international panel of governmental representatives and scientists to review the science of climate change, known as the "Intergovernmental Panel on Climate Change" (IPCC). IPCC has published numerous reports and that have become the source for such of the materials used in discussions and decision-making regarding the enhanced greenhouse effect.

At the 1992 Earth summit in Rio de Janeiro, about 151 countries signed the UN Framework Convention on Climate Change. The stated objective of the Framework Convention was to achieve

> "... stabilization of the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

The international political response to climate change began with the UN Framework Convention. The Kyoto Protocol (an international agreement linked to the United Nations Framework Convention on Climate Change, at 3rd meeting of the conference of parties in Kyoto, Japan in 1997) is generally seen as an important first step toward a truly global emission reduction regime that will stabilize greenhouse gas emissions, and provides the architecture for any future international agreement on climate change. This agreement sets the collective global target of reducing greenhouse gas emission (in particular carbon oxide, methane, nitrous oxide) by about 5% of 1990 levels by 2012.

Different countries have been launched or continued different strategy/mechanism through which international commitments will be met. For example, in Australia, the Greenhouse Challenge Plus (launched in March, 2005) is a cooperative effort between Australian industry and the Commonwealth Government to reduce greenhouse emissions through voluntary industry action. Around 780 Australian companies are part of the program. Another scheme allows carbon "pooling" so that growers of small forests can group together to participate in abatement programs. In Bangladesh, tree plantation has become a major annual event and festival involving government, NGOs, and local communities. This is adding significantly to carbon sequestration potential. In addition, the two-stock engines in transports were replaced by four-stock engines, and diesel engines were replaced by natural gas engines, to reduce pollutants and greenhouse gas emissions.

3.13 Climate Change and Crop Production

3.13.1 Meaning of Climate Change

Climate change means the variation of climate or its components at a global or regional level over time. It describes the variability or average state of the atmosphere or average weather over time scales (ranging from decades to millions of years). These variations may result from internal processes of the earth, external forces (such as sunlight), or human activities. Our climate is changing, and at a rate faster than we have experienced in the past. The scientists worldwide agree that the average temperature of the atmosphere surrounding the earth is increasing. Global warming is currently recognized as a threat of climate change.

3.13.2 Impact of Climate Change

3.13.2.1 General Impact on Society and Agriculture

Human activities are affecting the composition of the atmosphere, possible climatic effects due to solar or terrestrial infrared radiation fields, possible changes of cloud processes, global warming, and environmental effects. Gradual build up of greenhouse gases is bringing about changes of global climate.

Climate change is now considered as one of the most serious threats to the world's environment, with negative impacts expected on human health, food security, economic activity, water and other natural resources, and other physical infrastructure. Global climate varies naturally, but scientists agree that rising concentrations of anthropogenic greenhouse gas emissions in the atmosphere are leading to changes in the climate.

The global warming is disrupting the activities of the natural ecosystem and human societies. Possible impacts of climate change may be on the following:

- Physical
- Social
- Agricultural
- Economic aspects
- Ecosystem

3.13.2.2 Physical Impacts

Physical impacts include the following:

- Increase in surface temperature of the globe (land and sea)
- Increase of incidence of drought, flood, wildfire, and their intensity
- Breaking up of ice at the north and south poles and melting
- Melting glaciers
- Increase in severity of cyclone, hurricanes, and typhoons

Increased precipitation due to higher rates of evaporation may produce stronger and more frequent storms. The same increased evaporation could suck the land dry in other regions of the world causing widespread drought and famine.

3.13.2.3 Social Impacts

Climate change can create devastating social problem. The people from the low-lying (coastal) area may become refuge because of probable sea level rise, which may create a serious problem in the existing dense population. Other problems include the following:

- Agriculture and food supply is affected by drought, flood
- Loss of lives, homes, and livelihoods from the increased severity of storms (hurricanes, typhoons, tornados, etc.)
- Disease carrying insects can move from one place to anther (into new areas) as temperature increases

3.13.2.4 Agricultural Impact

Agricultural impact may include the following:

- Shifting of climatic zone (i.e., some species may no longer be able to survive in their current location)
- Shifting of crop season
- Alteration of crop rotation
- Impact on crop production

In the countries where agricultural production is highly dependent on rainfall (such as India, Bangladesh, Nepal), drought has direct effect on agriculture. Drought can reduce the countries food grain production as much as 15–20% of production of normal year.

3.13.2.5 Economic Impacts

Climate change may pose economic problem in a country. Extreme climatic events such as drought, typhoons, and consequent flash flood may destroy wealth, crops, and livestock. The poor regions may be severely affected by climate change as they have few resources to adapt.

3.13.2.6 Ecosystem

As a result of climate change, natural ecosystem may adapt readily or not. Certain species may be tolerant of only a narrow band of temperature and unable to move their range fast enough, could become extinct. Natural ecosystems will therefore become increasingly unmatched to their environment. They may also be prone to disease and attack by pests. Due to climate change, the changing output of land surface processes and feedback (when the output of a system affects the input) may affect hydrological and ecological processes. Warmer climate means decreased river flows. Consequently, higher temperature could harm the water quality of the rivers and lakes. In areas where river flows decrease, pollution concentration will rise because there will be less water to dilute the pollutants.

3.13.2.7 Impact on Crop Production

Climatic changes may affect the crop production through their direct and indirect effects on yield. As the productivity of a crop depends on genotype × environment interaction, crop development rate may be affected by modified/changed environment. Biophysical processes of agro-ecosystem are strongly affected by environmental factors. Among environmental factors, weather factors such as temperature (maximum and minimum, night temperature), soil moisture, and solar radiation are primarily important. Irrigation water demands are particularly sensitive to changes in precipitation and temperature. Global warming may alter not only temperature, but also cloudiness, windiness, and humidity as well. All these factors determine the atmospheric demand for water vapor or its drying power, hence the water demand. Thus, any change in climatic parameters due to global warming or climate change will also affect crop water demand.

The specific changing effects of weather elements on crop growth and yield are described below:

Carbon Dioxide

Carbon dioxide is the first molecular link from atmosphere to biosphere. Plant growth rate and photosynthetic capacity depend on the availability and utilization of atmospheric carbon dioxide. Increase in atmospheric carbon dioxide has a fertilization effect on crops with C3 photosynthetic pathway and thus promotes their growth and productivity. From a controlled environment study, Ali and Farage (1995) noted that due to increase in carbon dioxide (CO_2) concentration from 350 to 650 ppm, the total drymatter production of wheat increased by 160%. Tillers and leaf numbers increased significantly by CO_2 enrichment, and the plants showed greater leaf area ratio. Elevated CO_2 resulted in about 33% increase in root to shoot dry weight ratio. In case of unit leaf, increased CO_2 causes decrease in leaf stomata and resulting decrease in transpiration.

Temperature

Temperature influences on crop growth and yield in different ways, which are described below:

Through Availability of Water

The availability of water is one of the most important factors in plant growth. Because of increase of atmospheric temperature, the moisture holding capacity of the atmosphere increases, as a result the ET rate increases. If other components of weather remains the same, a 10% increase in temperature increases ET by 11–15% (Ali and Adham 2007). In addition, evaporation from bare soil increases with the increase in temperature. Consequently, in the regions where soil moisture storage is the only source of moisture to grow crop, the soil moisture may be depleted quickly and adverse impact on crop growth and yield. Besides, in many regions, crop production may become impossible during dry season.

Effect of Higher Temperature on Crop Adaptability, Growth Acceleration, or Deceleration

Crop productivity is inhibited at temperature higher than optimum, which also affects the adaptability of a crop or variety. The efficiency of temperature utilization varies with genotype as well as the location. In addition, there is an optimum temperature for each growth stage of crop. If the ambient temperature becomes higher than the optimum, the quality of the product may be lowered, for example tobacco, tea, etc. In temperature-sensitive plants, if the atmospheric temperature (particularly night temperature) attains above a certain critical level at particular stage(s), flowering occurs early and the yield is reduced.

If the water and nutrient supply are sufficient, the yield of some crops may be increased due to increased temperature. The plants absorb more water to satisfy ET, resulting in more nutrients. In the presence of sufficient solar radiation, more carbohydrate is prepared, and thus more dry-matter is produced.

Inhibition Through Low Temperature

If the temperature is lower than the optimum, plant growth is retarded and requires longer crop duration or maturity period. As a result, it may inhibit in increasing cropping intensity. Besides, if the temperature is decreased during flowering and pollination of some crops, the yield is reduced (e.g., Aman rice in Bangladesh).

A combination of lower temperature (within critical limit) along with sufficient (or higher) solar radiation leads to higher production. At low temperature, the respiration rate is reduced, thus less energy is lost and results in higher storage of Photosynthates (i.e., higher net assimilate accumulation and higher dry-matter production).

Relevant Journals

- Journal of Agrometeorology
- Agricultural and Forest Meteorology

- Solar Energy
- Solar Physics
- Hydrology Journal
- Journal of Hydrology
- Hydrological Processes
- Journal of Applied Hydrology
- Journal of Environmental Hydrology
- Journal of Hydrology and Hydromechanics
- Theoretical and Applied Climatology
- Climate Change
- Meteorology and Atmospherics
- Dynamics of Atmospheres and Oceans
- Advances in Atmospheric Sciences
- Agricultural Ecosystem and Environment
- Journal of Arid Environment
- Arid Zone Research
- Agronomy Journal

FAO Papers

- FAO Irrigation and Drainage Paper No. 37 (Arid Zone Hydrology)
- FAO Irrigation and Drainage Paper No. 27 (Agro-meteorological Field Stations)

Exercise/Questions

1. Discuss the importance of weather in water management
2. Explain the mechanisms of weather variability
3. Briefly describe how the weather factors influence the crop water demand
4. Discuss how the climatic factors affect crop production and crop adaptation in an area
5. Narrate the mechanism of rain formation
6. What are the temporal and spatial patterns of rainfall? Briefly describe the rainfall averaging techniques.
7. What is double mass curve of rainfall? Discuss the techniques of fill up gaps of rainfall and extending rainfall data.
8. Write short notes on: (a) Probability, (b) Exceedance probability, (c) Risk, (d) Maximum probable rainfall, (e) ARI, (f) Return period, (g) Dependable rainfall
9. Narrate the procedure for establishing a rainfall probability graph

10. Brief the rational method for computing peak runoff
11. Define and sketch (a) flood hydrograph and (b) unit hydrograph. Mention the steps for developing unit hydrograph from storm hydrograph.
12. Briefly discuss the evaporation process.
13. Sketch the scattering of incoming solar radiation. Classify the solar radiation that reaches to the earth.
14. Write short note on: (i) solar constant, (ii) albedo, (iii) solar declination, (iv) terrestrial radiation, (v) extra-terrestrial radiation.
15. Write down the equations for (a) Net radiation, (b) solar energy balance; and define the elements.
16. Why solar radiation is important? Write down different models for estimating solar radiation.
17. Write down the procedure for estimating photo-period.
18. Discuss the causes of temperature variation over locations and seasons.
19. What are the forms of expression of temperature?
20. Write down the forms of humidity expression
21. Explain the temporal and spatial variability of humidity.
22. Define air pressure. How air pressure is measured? Explain the implication of low and high air pressure.
23. Define wind profile. Mention different law/formula for converting wind speed measured at different height.
24. Write short note on: (i) ENSO, (ii) tropical storm, (iii) thunderstorm.
25. What are the essential parameters that should be measured in a weather station? Mention their respective measuring instruments.
26. Why weather forecasting is important for agricultural decision making? What are the common methods of weather forecasting?
27. Briefly explain the copping strategies for hazardous weather.
28. Narrate different agro-climatic indices. Mention their utility in crop ecology/crop calendar.
29. What is potential environmental yield? How it can be calculated?
30. Mention the suitability class for agro-climatic evaluation of rice.
31. What is green-house effect? Briefly explain the process of green-house gases development.
32. What are the possible consequences of green-house gases?
33. What is meant by climate change? Discuss the issues and impacts of climate change on society and crop production.
34. What is drought? What are the possible mitigation measures of drought?
35. An agricultural field is to be protected from the river-flood. It is suggested to design a retaining wall to retain one in 150 flood.
    (a) What is the chance of the crop field being flooded in the next 25 years of wall construction?
    (b) To lower the risk to 2%, what ARI flood should the wall be designed for?
36. Determine the peak flow rate from an area of 100 ha due to a rainfall of 150 mm? Assume runoff coefficient for the area as 0.6.

37. Estimate the day length using solar equation for a location of 23°S latitude for 15th July. Estimate global radiation on that day, assuming bright sunshine hour as 6. Assume standard value of any missing data.
38. Estimate R_g for a location having $T_{\max} = 32°\mathrm{C}$, $T_{\min} = 20°\mathrm{C}$. Assume standard value for any other missing parameters.
39. At a location, wind speed at 2-m height is 4 m/s and the roughness length is 1.0 cm. Find the velocity of air at 1-m height in that location.
40. Calculate the environmental potential yield of wheat for an area with the following information:

Crop	Effective growing period (period of capturing solar radiation)	Average solar radiation for the months (MJ/m^2/day)
Wheat	Nov, 1–Mar, 15	10, 9, 10.5, 13, 14

If the actual seed and straw yield of wheat are 5.5 and 7 t/ha, respectively, find out the scope to increase dry-matter production through improved cultivar (through breeding program).

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Chapter 4
Soil: A Media for Plant Growth

The role of soil in the soil–plant–atmosphere Continuum is unique. Although soil is not essential for plant growth and indeed plants can be grown hydroponically (in a liquid culture), usually plants are grown in the soil, and soil properties directly affect the availability of water and nutrients to plants. Soil water affects plant growth directly through its controlling effect on plant water status and indirectly through its effect on aeration, temperature, nutrient transport, uptake, and transformation. The knowledge of soil-water status and its movement in soil is important and has practical implications in agricultural, environmental, and hydrological situations. Soil-water movement in the field depends on the hydraulic properties of the soil. The understanding of these properties is helpful in good irrigation design and management.

4.1 Basics of Soil

4.1.1 Definition of Soil

Soil is a typical heterogeneous multi-phasic porous system, which, in its general form, contains three natural phasic components: (1) the solid phase of the soil matrix (formed by mineral particles and solid organic materials), (2) the liquid phase, which is often represented by water and which could more properly be called the soil solution; and (3) the gaseous phase, which contains air and other gases. Practically speaking, a soil particle must pass through a 2-mm sieve to be called soil particle. Soil particles are either organic or inorganic.

The soil particles are aggregated by organic matter, mineral oxides, and charged clay particles. The gaps between the particles link together into a meandering network of pores of various sizes. Through these pore spaces, the soil exchanges water and air with the environment. The movement of air and water also allows for heat and nutrient to flow.

M.H. Ali, *Fundamentals of Irrigation and On-farm Water Management: Volume 1*,
DOI 10.1007/978-1-4419-6335-2_4, © Springer Science+Business Media, LLC 2010

4.1.2 Agricultural Soil

The agricultural soil is one which, with the presence of nutrient and water, can facilitate plant growth.

4.1.3 Components of Soil

The primary components of soil are as follows:

(a) Minerals
(b) Water
(c) Air
(d) Organic matter

To understand soil and its behavior, we must first understand its composition (Fig. 4.1) and the interrelation among the components.

(a) Mineral

The mineral fraction of soil consists of the actual soil mineral particles. Traditionally, soil minerals are classified on the basis of their size. The USDA soil textural classification system divides minerals into sand, silt, and clay particles on the basis of their sizes, which are as follows:

Sand particle: 2–0.05 mm
Silt particle: 0.05–0.002 mm
Clay particle: <0.002 mm

We can realize the importance of size by comparing the number of particles for a given volume. In a 10 gm of soil sample, if all the particles are 1 mm sand particle, there would be approximately 7.2 thousands particle. The same weight of soil will require approximately 7.2 million silt-sized particles and 7.2 trillion clay-sized particles. Because of the large amount of fine particles in a small volume or weight of soil, the fines exert a large influence on the behavior of soil.

(b) Water

The second component of soil is water. Water exists as free liquid in the pores or voids between soil particles, or as thin films surrounding soil minerals.

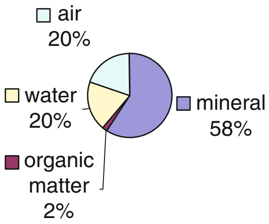


Fig. 4.1 Composition of an ideal soil

(c) Air

The third component of soil is soil-air. It is composed primarily of nitrogen, carbon dioxide, and oxygen. When the gravitational water drains away, the air fills the large voids or pores between the soil particles. As more water is used, more air is drawn into the soil. When rainfall or irrigation events occur, the air is forced out of the soil. The oxygen in the soil air is needed to support the growth of plant roots. Plant roots respire or breathe much like animals taking oxygen from the air and using it to oxidize sugars and carbohydrates to make energy needed for growth and the uptake of nutrients. Ideally, a soil should contain 15–30% air-filled pore space.

(d) Organic matter

The fourth component of soil is organic matter. It includes all materials that are primarily composed of carbon, hydrogen, and oxygen. The common or laymen's definition of organic matter would be "living, dead, or partially decayed plant and animal substances." This definition includes all the plants (live and dead plants) roots, rhizomes, and leaves. The entire soil microbial community is also a part of the soil organic matter pool.

Soil organic matter has many beneficial functions in soil such as retaining water, retaining nutrients, reducing the saturated hydraulic conductivity of sandy soils, and acting as a binding agent between soil particles to promote the formation of soil aggregates. Organic matter has a high cation exchange capacity (CEC), which allows it to attract and retain cations in an exchangeable form. The high CEC also tends to help buffer the soil pH and prevent much fluctuation in pH. Organic matter is effective in absorbing and retaining water and minimizing the potential to wash off of the soil with runoff. It serves as a food source for soil microbes and helps to maintain an adequate and healthy population of soil microbes. Finally, it acts or serves as a source of plant nutrients.

From the components of soil, it is observed that the soil consists of three types (phasics) of materials: solid, liquid, and gaseous. The solid part consists of soil particle (mineral) and organic matter, the liquid part consists of water and dissolved substances, and the gaseous part consists of air and/or water vapor. The soil is thus a complex system. Its solid matrix consists of particles differing in chemical and mineralogical composition as well as in size, shape, and orientation. The mutual arrangement or organization of these particles in the soil determines the characteristics of the pore spaces in which water and air are transmitted or retained.

4.1.4 Importance of Soil for Irrigation

Soil acts a media of water storage. The loss of water by plants to the atmosphere is an inevitable consequence of the necessity of a physical pathway for gaseous exchange through which CO_2 can be acquired from the atmosphere. Since few plants are capable of storing a significant fraction of the water that must be transpired daily, there must be a continuous replenishment of the plant water through the root system. The soil pores in the vicinity of the plant roots provide the reservoir by which this water is stored and through which it is transmitted to the roots.

Soils differ in their physical and hydraulic properties that determine in part the suitability for plant growth. This chapter deals with the principles of soil properties that are related to water absorption, retention, and transmission by soils; and methods for their determination/estimation, which must be understood if optimum value is to be realized for the management of such a system for irrigation and water management.

4.2 Physical Properties of Soil

For optimum plant growth, it is essential that the soil provides a favorable physical environment for root development that provides the plant's needs for water, nutrients, and anchorage. Other essential conditions include aeration, optimum soil temperature, seed emergence, root penetration facility (low mechanical impedance), etc.

4.2.1 Qualitative Description of Soil Physical Properties

Similar to other physical bodies, soils have unique properties that define them. The physical properties of a soil are those characteristics that can be seen with the eye or felt between the thumb and fingers. They are the results of soil parent materials being acted upon by climatic factors and affected by topography or life forms (kind and amount such as forest, grass, or soil animals) over a period of time. A change in any one of these usually results in a difference in the type of soil formed. While diagnosing whether a soil is healthy or not, or to differentiate one type of soil from another, the following physical properties can be found:

- Color
- Texture
- Tilth
- Depth
- Slope
- Drainage or drainability
- Water holding capacity
- Bulk density
- Structure
- Porosity

The physical properties and chemical composition largely determine the suitability of a soil for its planned use and the management requirements to keep it productive.

4.2.1.1 Color

The color of a soil can give idea to its health, origin, and long-term changes. It can also indicate the color of the parent material. Surface soil colors vary from almost white, through shades of brown and gray, to black. Light colors indicate low organic matter content and dark colors indicate a high organic material content. The more humus, the blacker the soil. Light or pale colors in the surface soil are frequently associated with relatively coarse texture, highly leached conditions, and high annual temperature. Distinct red and yellow colors usually indicate older, more weathered soils. Subsoil color can be a valuable indicator of how well the soil drains. The red to brown color of subsoils comes from iron coatings under well-aerated conditions.

4.2.1.2 Texture

Texture refers to the relative amount of differently sized soil particles (sand, silt, and clay), or the fineness/coarseness of the mineral particles in the soil. Texture is used only to describe the distribution of the inorganic fraction. Humus content has nothing to do with texture.

4.2.1.3 Tilth

Tilth refers to a soil's physical condition. A soil in good tilth is easily worked, crumbled, and readily takes in water when dry. Factors that influence a soil's tilth are texture, organic matter, and moisture content. Therefore, tilth can vary markedly with changes in moisture content, the amount of humus present, and compaction, especially if it is clayey.

4.2.1.4 Slope

A field's slope has a marked influence on the amount of water runoff and soil erosion caused by flowing water. Slope is usually measured in terms of percentages. A 10% slope has 10 m of vertical drop per 100 m horizontal distance. Soil conservation measures become necessary on land with little of a slope as 1–2% to avoid problems.

4.2.1.5 Depth

Soil depth indicates how deep (top to bottom) the topsoil plus the subsoil is. Depth can be determined by digging a hole. Soil depth is important for plants because deeper rooting means more soil to exploit for nutrients and water. Greater soil depth can also mean better drainage, as long as there are no restrictive layers in the subsoil. Soils may be classified as being deep or shallow as follows:

Class	Depth (topsoil + subsoil) (cm)
Very shallow	<25
Shallow	25–50
Moderately deep	50–75
Deep	75 or higher

4.2.1.6 Water Holding Capacity and Drainability

Field water-holding capacity is the amount of water that a soil can hold after being saturated and allowed to drain for a period of 1–2 days. Field water-holding capacity is influenced by soil texture, aggregation, organic matter content, and overall soil structure.

Drainability refers to a soil's ability to get rid of excess water, or water in macropores, through downward movement by gravity. Heavy clay soils that have a lot of micro-pores have a higher water-holding capacity, but because they have fewer macro-pores, their drainage is poor.

4.2.1.7 Bulk Density

Soil bulk density is the mass of soil per unit volume. Bulk density provides an estimate of total water storage capacity, texture, infiltration rate, compactness, or aeration condition. It also gives useful information in assessing the potential for leaching of nutrients, erosion, and crop productivity. Bulk densities that limit plant growth vary for soils of different textural classes. There is a clear inverse relation between density and porosity.

4.2.1.8 Specific Heat Capacity

Specific heat capacity varies with texture. As sandy soils hold very little water, they warm up faster in the summer and cool down sooner in the winter. In contrast, clay soils with higher water content have high specific heat capacities. They warm up slower in the summer and cool down slower in the fall.

4.2.2 Description and Measurement Techniques of Important Soil Physical Properties

4.2.2.1 Bulk Density

Understanding Soil Density
In three-phase (solid, liquid, and gaseous) soil system, the concept of average density can be defined as follows: (1) density of the solids or soil particle density, (2) bulk or dry density, and (3) total or wet density.

Within a certain volume of soil, the total mass (M_t) can be defined as:

$$M_t = M_s + M_l + M_g,$$

where M_s is the mass of solid, M_l is the mass of liquid, and M_g is the mass of gases.

But the mass of gases is negligible when compared with the masses of the solid and liquid phases, and thus ignoring M_g,

$$M_t = M_s + M_l.$$

Similarly, within a certain volume of soil, the total volume (V_t) can be defined as:

$$V_t = V_s + V_l + V_g,$$

where V_s is the volume of solid, V_l is the volume of liquid, and $V_g$is the volume of gases.

Definition of Soil Bulk Density

Density, as applied to any kind of homogeneous mono-phasic material of mass (*M*) and volume (*V*), is expressed as the ratio of mass to volume (i.e., *M*/*V*). Under specific condition, this definition leads to unique values that represent a well-defined property of the material. However, for heterogeneous and multi-phasic materials, such as porous media, application of this definition can lead to different values.

The soil bulk density or dry density is a measure of the weight of the soil per unit volume (including pore space), usually given on an oven-dry (105°C) basis. It can be defined as the ratio of the mass of the solid phase of the soil (i.e., dried soil) to its total volume (solid and pore volume together). That is, bulk density,

$$\begin{aligned}\rho_b &= (\text{dry soil mass})/(\text{bulk soil volume})\\ &= \frac{M_s}{V_t} = \frac{M_s}{V_s + V_l + V_g}.\end{aligned}$$

Just as soil is a combination of soil minerals, organic matter, and air- or water-filled pores, bulk density is a weighted average of the densities of its components:

$$\rho_b = f_a\rho_a + f_p\rho_p + f_o\rho_o,$$

where *f* is the volume fraction of a component, a is the air (pores), p is the soil mineral particles, o is the organic matter, and ρ_a, ρ_p, and ρ_o are the densities of air, mineral, and organic mater (fractional) components.

Factors Affecting Bulk Density

Bulk density is primarily a function of relative pore space and organic matter content. Variation in bulk density is attributable to the relative proportion and specific gravity of solid organic and inorganic particles and to the porosity of the soil. The factors affecting bulk density are as follows:

- Degree of aggregation (or degree of compactness or looseness)
- Structure of the soil matrix
- Soil texture
- Organic matter content
- Presence of heavy elements, such as iron compound
- Moisture content
- Soil matrix's swelling and shrinkage characteristics

Management factors that influence bulk density are tillage, organic amendments, cropping intensity, adding or removing residue, trafficking on wet soil, etc.

As the density depends on compactness, the bulk density of a cropped soil is not a constant value, but varies from sowing/transplanting to harvest, depending on the irrigation events and other cultural practices. At sowing, the bulk density is generally low (1.0~1.3), increases after irrigation and drying. Subsoils are generally more compacted because of the overlying weight of the soil. They usually have less organic matter to build the more open granular structure. In general, the bulk density of a soil increases with profile depth (Fig. 4.2) because of changes in organic matter content, porosity, and compactness. Often subsoil accumulates clays and iron oxides, which have been eluviated from upper horizons. These clays are often trapped in large pores, thereby reducing the overall pore space. For the same compaction, coarse textured soils will usually have a higher bulk density because they have less pore space than fine textured soils.

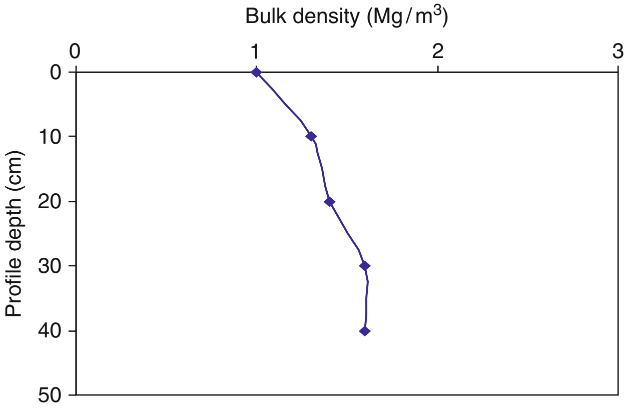


Fig. 4.2 Changing pattern of bulk density with profile depth

Typical Values of Bulk Density

The dry or bulk density of most soil varies within the range of 1.1–1.6 Mg m^{-3}. An average value would be 1.3 Mg m^{-3} for loamy soil.

Importance of Bulk Density

Bulk density is a fundamental soil property. It is an important property of soil since it affects how easily plant roots can penetrate the soil when the roots propagate. Soil bulk density data are necessary in calculating soil moisture movement within a profile, and rates of clay formation and carbonate accumulation. To convert soil moisture in percent weight (% w/w) to percent volume (% v/v), multiply by bulk density. Furthermore, it is used to calculate soil porosity. It is also an essential piece of information for converting laboratory chemical data, which is commonly on a per unit mass basis (e.g., mgCa per kg soil), to volume (or area × depth) units (kgCa per ha in the 0–30 cm).

Determination of Bulk Density

In determining bulk density, it is to be ensured that only the mass of soil <2-mm particle has been included (the numerator of the fraction or equation). The same is true for soil volume in the denominator. That means that coarse fraction must be subtracted from total volume, which requires assuming a rock particle density (usually 2.65 Mg m^{-3}).

Several techniques available to determine the bulk density are as follows:

Direct measurement

(a) Core method
(b) Clod method
(c) Excavation method

Indirect method

(d) Radiation method
(e) Regression method

Core Method

The determination usually consists of drying and weighing a soil sample, the volume of which is known (volume of the core). It can be easily measured by gently pressing a small cylinder (core) into the soil, removing the core (containing soil), and weighing, drying to remove the water contained in the pore space and weighing.

The working procedure is given below:

- Cylindrical metal or plastic coring tools (of known volume or volume must be determined) are selected and numbered (for depth and replication).
- A lubricating material is used to lubricate the inner side of the cores for minimizing the friction force during insertion in soil.
- The core is driven into the soil to a desired depth.
- The soil surrounding the core is removed and the intact core is removed carefully, so that the soil inside the core remains intact.
- The excess soil, if any, is removed by a sharp knife to avoid smearing effect.
- The core is covered by polythene and carried to the laboratory.
- It is then dried in an oven at 105°C, unless constant weight is achieved (about 36–48 h)
- Then it is weighed (soil + core) with an electronic balance having $2\sim3$ decimal point.
- After removing the soils from the core, the empty core is weighed.
- Then the bulk density is calculated from the formula:

Bulk density = (weight of dry soil)/(volume of dry soil)

Calculation sheet for determining bulk density using core method:

Sl. no.	Wt. of oven-dry soil + core (gm)	Wt. of core (gm)	Core volume			Actual soil vol.[a] (cm^3)	Wt. of oven-dry soil (gm)	Bulk density (gm/cm^3)
			Height, h (cm)	Dia, d (cm)	Vol. = $\pi d^2 h/4$			
	(1)	(2)			(3)	(4)	(5) = (1)–(2)	(6) = (5)%(4)
1	160	25	6	5	117.8	117.8	135	1.15

[a] If the soil volume is less than the core volume (somehow some soil is dropped out), then the blank volume should be estimated by filling with sand, and then the sand should be poured in small calibrated volumetric cylinder; and the volume should be deducted from the core volume [i.e., (4) = (3) − volume of lost soil]

Advantages of core method:

- The equipment is relatively simple
- Undisturbed soil can be obtained

Disadvantages:

- Small sampling area of core
- Stones or other hard material can hamper the sampling
- Compression of soil inside the core may happen if the edge of the core is not sharp and inner surface is not smooth

A large diameter core diminishes the disadvantages, except in soils having rocks (that are large and closely packed).

Clod Method

The clod method is a laboratory method. The bulk density of the clods or peds can be calculated from their mass and volume. The volume may be determined by coating a clod of known weight with a water-repellent substance (such as paraffin, saran rubber, or wax mixtures) and weighing it first in air, then again while immersed in a liquid of known density, making use of Archimedes' principle. The clod must be sufficiently stable to cohere during coating, weighing, and handling. The working procedure is as follows:

- Take several peds from each sampling depth having volume of about 10~30 cm^3
- Tie each ped with thread so that it can be hanged freely
- Place the ped in a weighed and numbered beaker
- Place the beaker (containing the ped) in an oven and allow them for about 24 h
- Remove the beaker from the oven, cool in the dessicator, and weigh the beaker containing ped
- Immerge the ped in the melted paraffin (or other coating solution), take it out and allow to dry
- Weigh the coated ped and record its weight
- Immerge the ped in water hanging from a balance and weigh, or immerged the ped through the thread in a graduated beaker containing water and record the level of water before and after immersion. Also record the temperature of water.

Working data sheet:

ID no.	Fresh wt. of clod (gm)	Wt. of beaker (gm)	Wt. of beaker and dry-clod (gm)	Wt. of dry clod (gm)	Wt. of coated dry clod (gm)	Wt. of coated clod in water (gm)	Temp of water	Wt. loss in water (= wt. of displaced water) (gm)	Vol. of clod (= vol. of disp. water) (cm^3)	Bulk density (gm/cm^3)
	(1)	(2)	(3)	(4) = (3)–(2)	(5)	(6)	(7)	(8) = (5)–(6)	(9)=(8)/ρ	(10) = (4)/(9)
	40	20	45	25	29	13	26	16	16.3	1.53

Note: ρ = density of water at measured temperature

For next option (immersion in water), the data sheet is:

ID no.	Fresh wt. of clod (gm)	Wt. of beaker (gm)	Wt. of beaker and dry-clod (gm)	Wt. of dry clod (gm)	Wt. of coated dry clod (gm)	Vol. of water in beaker (cc)	Vol. of water after insertion of clod (cc)	Vol. of coated clod (cc)	Correction for paraffin	Vol. of dry clod (cc)	Bulk density (gm/cc)
	(1)	(2)	(3)	(4) = (3)–(2)	(5)	(6)	(7)	(8) = (7)–(6)	(9)	(10) = (8)–(9)	(11) = (4)/(10)
	45	21	47	26	30	400	421	21	1.1	19.9	1.31
	…										

Advantage:

- Gives more accurate results than the core method if done properly.

Shortcoming:

- Peds on or near the soil surface are likely to be unavailable, because of tilling or plowing in crop fields.
- Care is needed to get naturally occurring ped or clod.

- The difference of the weight of the thread or wire in air and water requires correction.
- Greater number of samples should be used for each depth to reduce the error.

Excavation Method

It is a new technique to determine the density of field soil. Where surface soil is often too loose to allow core sampling, or where abundant stones preclude the use of core samplers, excavation method is the best choice.

The working procedure for this method is given below:

- Select a representative location
- Level the soil surface
- Dig a hole to the desired depth and collect the soil in a try or other container
- Dry the excavated soil in oven (at 105°C), and then weigh
- Line the excavated hole with polythene
- Fill the hole with measured volume of water
- Record the volume of water
- Calculate the bulk density as:

$$\text{Bulk density} = (\text{weight of dry soil})/(\text{volume of water required to fill the excavation})$$

Advantages:

- Easy to understand
- Give more accurate estimate than the core method if properly done
- Accuracy can be increased if large excavation (e.g., $12'' \times 12'' \times 6''$) can be made
- No problem in stony or gravelly soils

Disadvantage:

- Correction for volume of polythene may be necessary for obtaining accurate result

Radiation Method

The radiation method is an in situ method. In this method, transmitted or scattered gamma radiation is measured and with suitable calibration, the density of the combined gaseous–liquid–solid components of a soil mass is determined. Correction is then necessary to remove the components of density attributable to liquid and gas that are present.

Advantage:

- Once the calibration is performed, it is an undisturbed method and suitable for measurement during crop period.

Disadvantages:

- It is an indirect method.
- Requires a value of soil water content, and a calibration curve derived from soils with a known bulk density.

Regression Method (Indirect Estimation of Bulk Density)

Within a geographical region and for soils of a similar genesis, the close relationship between soil organic matter content and bulk density may allow use of regression equations to calculate the bulk density. For example, Federer et al. (1993) derived an equation for Northern Hemisphere tilt soils as:

$$\ln(\mathrm{BD}) = -2.314 - 1.0788\ \ln(\mathrm{OM}) - 0.1132[\ln(\mathrm{OM})]^2,$$

where ln is the logarithmic function, BD is the bulk density, and OM is the organic matter.

As the bulk density varies with compactness, it should be calibrated at each cultural situation (i.e., at sowing time, after irrigation, and after harrowing or weeding).

Examples on Bulk Density and Moisture Determination

Example 4.1. A sharp-edged cylinder of 5 cm in internal diameter is carefully driven into the soil so that negligible compaction occurs. An 8-cm column of soil is secured. The wet weight is 280 gm and the dry weight is 230 gm. Determine the following:

(a) The moisture percentage on a dry weight basis
(b) The apparent specific gravity of the soil
(c) Percent moisture on volume basis

Solution. Internal diameter of cylinder, $d = 5$ cm

Length of soil column, $h = 8$ cm
Volume of soil = $\pi d^2 h/4 = \pi(5)^2 \times 8/4 = 157.08\ \mathrm{cm}^3$
Weight of water after drying = 280 − 230 = 50 gm

(a) Moisture percentage on dry weight basis = (50/230) × 100 = 21.7
(b) Apparent specific gravity of the soil = 230/157.08 = 1.46
(c) Percent moisture on volume basis = 21.7 × 1.46 = 31.8

Example 4.2. A cylinder was carefully pushed into the soil without disturbing the soil. The cross-sectional area of the cylinder was 40 cm^2. The length of the column of soil within the cylinder was 30 cm. The weight of the soil within the cylinder was

1.65 kg when it was dried. The weight of the soil before drying was 2.0 kg. Determine the following:

1. Bulk density of soil
2. Percent moisture in weight basis
3. Percent moisture in volume basis

Solution. Volume of soil = $A \times h = 40 \times 30 = 1{,}200\ \text{cm}^3$

Wet of dry soil = 1.65 kg = 1,650 gm

1. Bulk density of soil = wt. of dry soil/vol. of soil = 1,650 gm/1,200 $\text{cm}^3 =$ 1.38 gm/cm^3
2. Wet of water = 2.0 − 1.65 = 0.35 kg = 350 gm

$$\begin{aligned}\text{Percent moisture in weight basis} &= (\text{wt. of water/wt. of dry soil}) \times 100\\ &= (350\text{gm}/1{,}650\text{gm}) \times 100\\ &= 21.2\end{aligned}$$

3. Percent moisture in volume basis = Percent moisture in weight basis × bulk density = 21.2 × 1.38 = 29.2

4.2.2.2 Particle Density

Particle density represents the density of the soil (i.e., mineral) particles collectively. Real density or particle density or density of solids (D_p or ρ_s) is the weight of a given volume of solids only, which is given as,

$$\rho_s = M_s/V_s,$$

where M_s is the mass of solids and V_s is the volume of solids.

Particle density would be equivalent to the average density of the soil minerals and the organic matter. It varies between 2.6 and 2.7 Mg/m^3. An average value of 2.65 is generally used. The presence of iron oxides and other heavy minerals increases the value of the soil particle density, and presence of solid organic materials in the soil decreases the value.

4.2.2.3 Soil Texture

Concept

Soil texture refers to the distribution of the soil particle sizes. From the proportions of the three particle sizes, soils get their textural names. Usually, the textural class is determined from the MARSHAL Triangle (Fig. 4.3). In each textural class, there is

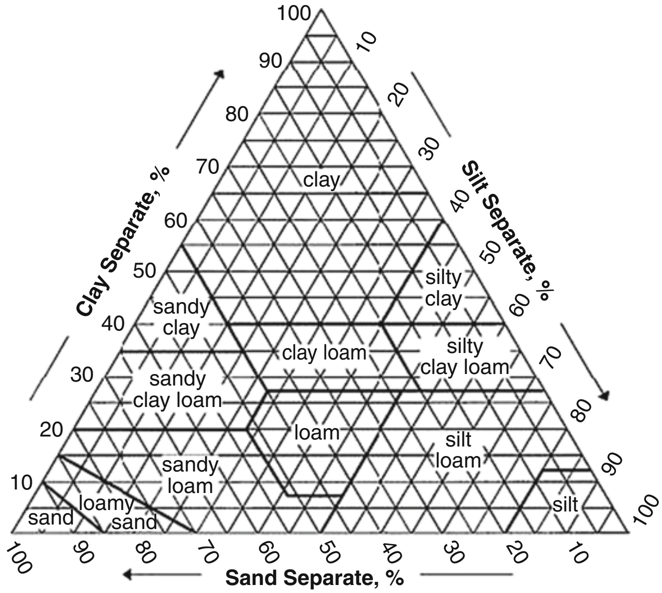


Fig. 4.3 Marshall's triangular co-ordinate for soil textural class

a range in the amount of sand, silt, and clay that class contains. Each class-name indicates the size of the mineral particles that are dominant in the soil. Loam is a textural class of soil that has moderate amounts of sand, silt, and clay. It contains about 7–27% clay, 28–50% silt, and 23–53% sand. An ideal soil texture would be 40% sand, 40% silt, and 20% clay.

Soil texture affects water retention, aeration, specific heat capacity, fertility or CEC, etc. Sandy soils have the coarsest texture and therefore the largest pore sizes. These large pores drain rapidly, and the sand particles do not compact; therefore, these soils have the highest aeration volumes, and the clay soils have the lowest aeration volumes (Table 4.1).

A soil's texture has a big influence on its productivity and management needs because it affects tilth, water-holding capacity, drainability, erosion potential, and soil fertility. It also determines the water release property of soil.

The term *duplex*(texture-contrast soil) is used to describe soils with a distinct texture increase in their profile. Top soils can vary from sandy to heavy loams with a great range of inherent chemical stabilities and structure, and similar variation exists in the properties of subsoils.

Analysis of Particle Size

Particle size analysis of soil refers to the process of determining the amounts of individual soil separates, which are below 2 mm in diameter. Different methods are available to analyze particle size:

Table 4.1 Differential properties of different textured soils

Property	Texture		
	Sand	Silt	Clay
Bulk density (g/cm^3)	Low (1.0–1.10)	Medium (1.1–1.3)	High (1.3–1.6)
Porosity (% void)	Low	Medium	High
Pore size	Large (mostly large pores)	Medium (small pores predominate)	Small (small pores predominate)
Soil particle surface (surface area for a given volume)	Small	Medium	Large
Water holding capacity	Low	Medium	High
Permeability	Rapid (>10 mm/d)	Slow to moderate (2–8 mm/d)	Slow (~2 mm/d)
Field capacity/upper limit of plant available water	Low (<35% v/v)	Medium (<45% v/v)	High (45–55% v/v)
Wilting point/lower limit of plant available water	Low (<15% v/v)	Medium (<20% v/v)	High (20–30% v/v)

(a) Hydrometer method
(b) Pipette sampling method
(c) Finger feel method

Hydrometer Method

This method is also known as Bouyoucos Hydrometer method. It is a very common method of soil particle size distribution (or mechanical) analysis. In this method, a hydrometer is inserted in the sample soil–water mixture (suspension), which indicates the stage of settlement. According to the Archimedes's principle, it indicates the density of the mixture at the position of hydrometer bulb, which in-turn relates to the amount of sediment still suspended at that depth. As the particles continue to settle out, the hydrometer will fall further deeper in the solution.

Collection of soil samples is an important aspect for mechanical analysis. Soil samples should be collected from different places and mixed together, dried and brought to powder form by hand grinding. Pulverized sample is then sieved through 20-mesh sieve and a part of the sample is then taken for mechanical analysis. The working method is as follows:

- Take 50 gm of soil in a dispersion cup
- Add sufficient water to cover the soil
- Add 10 gm of dispersing agent, such as calgon, sodium carbonate, sodium hydroxide, or sodium oxalate
- Allow about 15–20 min for reaction (clay soil may require higher time, 30 min)
- Add water to the dispersion cup (about 2/3 of the cup) and stir for 10 min with electric stirrer
- Transfer the mixture to a 1,000 ml cylinder (wash the dispersion cup to ensure transfer of any remaining settled particles)

- Add water up to the mark of 1,000 ml, and put a cork on the mouth of the cylinder
- Invert and shake the cylinder several times to ensure proper mixture of the solution, and keep on the table for allowing sedimentation of the suspended particles
- Insert the hydrometer into the suspension at 40 s and 2 h (in ISSS) (5 min and 5 h for ASTM) from the starting of sedimentation. Measure the temperature of the solution each time.

Temperature correction of the hydrometer reading:

The hydrometer is calibrated at 68°F. Deviation from this temperature needs correction of the reading. Add or subtract 0.2 units for every degree above or below 68°F, respectively.

Let the corrected reading at 40 s $= A$

Corrected reading at 2 h $= B$

Wt. of soil sample $= W$ gm

Then, % Clay + % Silt $= \frac{A(\mathrm{g/l})}{W} \times 100$

$$\%\,\mathrm{Clay} = \frac{B}{W} \times 100,$$
$$\%\,\mathrm{Sand} = 100 - (\%\,\mathrm{Clay} + \%\,\mathrm{Silt}),$$
$$\%\,\mathrm{Silt} = 100 - (\%\,\mathrm{Clay} + \%\,\mathrm{Sand}).$$

Modifying Soil Texture

The question may arise whether the texture of the soil can be modified or not. Before answering this question, it is to be mentioned here that texture refers to the percentage of sand, silt, and clay. It is possible to modify the texture on a small scale by adding sand or clay to the existing soil, but it is not practical to modify the texture on a large scale. For example, the quantity of sand required to significantly change the texture of a clayey soil would be enormous and therefore impractical. But due to the passage of time (20∼30 years) and cultural practices (tillage and cropping, adding fertilizer), the sand particles break down to smaller one, and thus the sandy texture tend to change to loam or silt.

4.2.2.4 Soil Structure

Concept

Soil structure refers to the arrangement of soil particles into certain patterns. The organic material, together with the fine soil particles, contributes to aggregate formation, which results in the improvement of the soil structure. The structural pattern, the extent of aggregation, and the amount and nature of the pore space describe the structure of the particular soil.

Characterization

Soil structure is dynamic and may change greatly from time to time in response to changes in natural conditions, biological activity, and soil management practices. The arrangement of soil particle is very complex and there is no practical way to measure a soil structure directly. The methods that have been proposed for the characterization of soil structure are indirect methods, which are affected by the structure rather than the structure itself. Thus, the concept of soil structure is used in qualitative sense, not quantitative.

Significance

Soil structure influences plant growth indirectly. The pores are controlling factor governing air, water, and temperature in soil, which in turn governs the plant growth. One of the effects of soil structure on plant growth is the emergence of seedlings in the seedbed. Roots of seedlings can not penetrate through the hard compact layer.

4.2.2.5 Porosity

Definition. *Porosity refers to the portion of the soil volume that is occupied by the pore spaces or voids. It is normally expressed as percentage of soil volume.*

$$\rho_t = \frac{V_p}{V_b} \times 100,$$

where ρ_t *is the porosity,* V_p *is the volume of pore, and* V_b *is the bulk soil volume. The air and soil-water solution move through these pores and also stored. Pores in soil can be classified into two types:*

1. *Macro-pore*
2. *Micro-pore*

Pores having diameter larger than 0.06 mm are called macro-pores. Pores having diameter less than 0.06 mm are called micro-pores. Most macro-pores exist between aggregates and are active in movement of air and water. The micro-pores that exist inside individual aggregates do not allow air and water to flow readily. In dry soil, some micro-pores still hold moisture, but surface tension effects are so high that plant roots can not extract it.

Factors Affecting Porosity

The factors that can have a great effect on porosity are the following:

- Texture
- Structure

- Organic matter content
- Compaction of soil (e.g., wheels of heavy machinery, natural setting, compaction after irrigation, by human movement, etc.)
- Management practices that reduces organic matter (e.g., continuous cropping will reduce the granular structure of soil and lower the pore space)
- Plant root system (cropping practices that include deep rooted plants will tend to improve porosity)

Coarse textured sandy soils have larger pores than fine textured soil, but less pore-space or porosity.

Estimation of Porosity

Porosity or pore space of soils can be calculated simply from the bulk density (D_b) and real or particle density (D_p).

$$\text{Porosity} = 1 - D_b/D_p.$$

For example, a soil has a real density of 2.6 Mg/m^{3}and a bulk density of 1.4 Mg/m^3. Then expressing in percent,

$$\%\ \text{porosity} = [1 - (1.4/2.6)]100 = 46.1\%$$

Typical Values of Porosity

Typical values of porosity for different types of soil are given below:

Texture	Porosity (%)
Sandy	30–40
Loam	40–45
Clay	45–55

Relation Between Bulk Density, Particle Density, and Porosity

The bulk density is related to the soil particle density by the porosity according to the following equation:

$$\rho_b = (1 - \rho_t)\rho_s, \tag{4.1}$$

where ρ_b is the bulk density, ρ_t is the porosity, and ρ_s is the particle density.

From the above equation, it is obvious that the value of bulk density is smaller than the value of the soil particle density. If the volume of the pores occupies half of the total volume, the value of dry or bulk density is half the value of the soil particle density.

Relationship Between Porosity and Void Ratio

Porosity, $\rho_t = V_p / V_b$; where V_p is the volume of voids and V_b is the bulk volume of soil.

Void ratio

It is the ratio of volume of voids to the volume of solids. That is,

$$r_v = \frac{V_p}{V_s}.$$

Volume of voids or pores = total bulk volume − volume of solid = $V_b - V_s$. Thus,

$$r_v = \frac{V_b - V_s}{V_s} = \frac{V_b}{V_s} - 1,$$

or,

$$1 + r_v = \frac{V_b}{V_s}. \tag{4.2}$$

4.2.2.6 Mechanical Impedance

Mechanical impedance occurs when the soil is lack of pore spaces of appropriate size, hard for the growing of roots to grow through or emerging shoots to push out of the way. Mechanical impedance may be caused due to the following:

- Inherent soil properties (cohesive soil)
- Poor soil structural condition
- Farm equipment operations
- Development of plough pan
- Low organic matter and high clay content
- Animal traffic under wet condition

Soil impedance can be assessed indirectly with some measures such as bulk density. It is usually quantified with some measures of soil strength (e.g., tensile or shear strength). Most widely used instrument is "Penetrometer." It is a device that when forced into the soil measures the resistance to penetrate to the soil. Here, the term "resistance" refers to the force exerted by the penetrometer, divided by its cross-sectional area.

Deep tillage, addition of organic matter and crop residues, and other measures that improve soil structure can reduce impedance and improve the soil physical environment for root growth.

4.2.3 Infiltration

4.2.3.1 Concept

The term “infiltration” refers to the process by which water enters into the soil body *or* mass from the soil surface. Infiltration rate indicates how fast water enters the soil. Mainly three forces govern infiltration:

- Gravity
- Suction
- Capillary action

Although smaller pores offer greater resistance to gravity, very small pores pull water through capillary action in addition to and even against the force of gravity.

4.2.3.2 Infiltration Rate, Infiltration Capacity, and Other Relevant Terminologies

Infiltration rate is a measure of the rate at which a particular soil is able to absorb rainfall or irrigation. It is measured in inches per hour or millimeter per hour. The rate decreases as the soil becomes saturated. It is related to the saturated hydraulic conductivity of the near-surface soil. The maximum rate at which water can enter a soil in a given condition is the infiltration capacity. If the precipitation rate exceeds the infiltration capacity, runoff will usually occur unless there is some physical barrier.

Some other relevant terminologies:

Water input rate. It is the rate at which water enters the soil surface.

Depth of ponding. It is the depth of water standing on the surface.

Sorptivity. It is the rate at which water will be drawn into an unsaturated soil in the absence of gravity force.

Intake rate. The rate of water absorption by soil from the furrow is termed as intake rate.

4.2.3.3 Significance of Infiltration

Infiltration is a physical property of soil, which is of great importance to irrigators and soil scientists. Infiltration process plays a conspicuous role in hydrology and thus also in watershed and agricultural water management. It is useful in generating runoff from rainfall (overland flow), flood prediction (i.e., losses in stream and channels), and groundwater recharge. In watershed management studies, infiltration indices obtained from soils under various types of vegetation cover and land use are helpful in providing a basis for judgment so as to optimize watershed conditions for water yield and soil erosion. Infiltration is also considered to be the basic criterion in the flow design of surface irrigation system such as boarder, furrow, sprinkler and drip, because it gives the estimate of intake rate.

4.2.3.4 Factors Affecting Infiltration

Infiltration is influenced by soil and fluid properties, flow conditions, and management practices.

The soil and land factors include the following:

1. Texture
2. Porosity
3. Bulk density
4. Organic matter content
5. Entrapped air
6. Soil crusting, compaction, cracks
7. Vegetation/vegetative cover
8. Initial moisture content
9. Slope of the field
10. Depth to ground water table
11. Land use

Fluid Factor

Fluid factors affecting infiltration include the following:

- Viscosity of fluid
- Turbidity of fluid

Flow Condition

Besides the soil and fluid properties, infiltration is also influenced by the flow conditions such as hydraulic gradient, depth of surface flow, duration of flow, velocity of flow, and rainfall intensity.

Management Practices

Management practices that affect soil crusting, vegetative cover, and soil porosity will increase or decrease the rate of water infiltration. For example, slow infiltration can be caused by increased soil compaction. Leaving crop residues on the surface or increasing the organic matter content in the soil surface may maintain aggregation and enhance infiltration.

The rate of infiltration is affected by soil characteristics including ease of entry, storage capacity, and transmission rate through the soil. The soil texture and structure, vegetation types and cover, water content of the soil, soil temperature, and rainfall intensity all play a role in dictating infiltration rate and capacity. For example, coarse-grained sandy soils have large spaces between each grain and allow water to infiltrate quickly. Infiltration capacity declines rapidly during the early part of a storm and then tends to constant value, referred to as *basic infiltration rate*. The mechanism behind such behavior is that the infiltrated water fills the available storage spaces and reduces the capillary forces drawing water into the pores. Clay particles in the soil may swell as they become wet and thereby reduce the size of the pores. In areas where the ground is not protected by a layer of forest litter, raindrops can detach soil particles from the surface and wash fine particles into surface pores where they can impede the infiltration process. Soil crusting, compaction, root and earthworm channels also influence the ability of water to move (infiltration) through soil surface and layers.

The process of infiltration can continue only if there is room available for additional water at the soil surface. The available volume of additional water in the soil depends on the porosity of the soil and the rate at which previously infiltrated water can move away from the surface through the soil. If the arrival of the water at the soil surface is less than the infiltration capacity, all of the water will infiltrate. If rainfall intensity at the soil surface occurs at a rate that exceeds the infiltration capacity, ponding begins and is followed by runoff over the ground surface, once depression storage is filled. This runoff is called Horton overland flow. The entire hydrologic system of a watershed is sometimes analyzed using hydrology transport models, mathematical models that consider infiltration, runoff and channel flow to predict river flow rates and stream water quality.

4.2.3.5 Typical Infiltration Curve

The characteristics of the typical infiltration curve are shown in Fig. 4.4. The infiltration rate is high in the early stages of infiltration (due to sorption) but tends to decrease monotonically and approaches a constant value, which is often termed as basic infiltration rate or final infiltration capacity.

The infiltration rate of water into soil seems to follow a power function during early period (time depends on soil) and then begins to deviate and approach a constant value of infiltration. Some general (typical) values for infiltration into soils of varying textural classes are presented in Table 4.2.

4.2.3.6 Infiltration Conditions

Infiltration is governed by water input rate (rainfall or irrigation water supply) and ponding depth as follows:

(a) When there is no ponding water on the soil surface, infiltration rate, $f(t)$ will be equal to the water input rate $w(t)$, until the water input rate is less than or equal to the infiltration capacity, f_c.

That is, if $H(t) = 0$, $w(t) \leq f_c$, then $f(t) = w(t)$

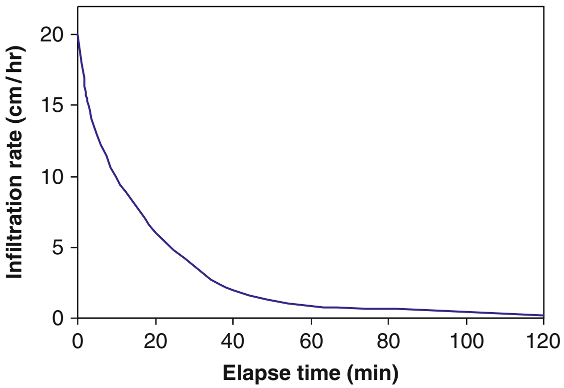


Fig. 4.4 Typical infiltration curve

Table 4.2 Typical steady infiltration rates for general soil textural groups

Soil type	Steady infiltration rate (cm/h)
Sandy soil	>2.0
Sandy loam	1.0–2.0
Loam	0.5–1.0
Silt loam	0.5–0.8
Clayey soil	0.1–0.5

(b) When there is ponding water on the soil surface or the water input rate is greater than the infiltration capacity, the infiltration rate will be equal to the infiltration capacity.

That is, if $H(t) > 0$, or $w(t) \geq f_c, f(t) = f_c$.

4.2.3.7 Mathematical Statement of Water Movement in Soil

Darcy's Equation

Darcy's law states that the flow rate (Q) through a media is directly proportional to the hydraulic gradient between the flow sections [$(h_1 - h_2)/L = dh/L$]. Mathematically, this is expressed as:

$$Q \infty A \frac{h_1 - h_2}{L}$$

or

$$Q = KA \frac{dh}{L}, \tag{4.3}$$

where K is a constant of proportionality. Darcy deduced that the value of K was related to the ability of the medium to transmit fluid. Thus, K is referred to as hydraulic conductivity and represents the properties of porous material and the properties of the fluid.

Flow per unit area, q is:

$$q = \frac{Q}{A} = \frac{KA\frac{dh}{L}}{A} = K\frac{dh}{L}. \tag{4.4}$$

Movement of water in soil occurs in liquid as well as vapor phase. In an unsaturated state, the soil macropores are filled with air. Since the soil air of a moist soil is of high relative humidity (nearly 100%), water moves within the soil in the vapor phase. Water also moves out of the soil by evaporation.

Richards' Equation

Richards' (1931) had derived the partial differential equation to describe the movement of water on the basis of Darcy's law and Buckingham's (1907) concept of capillary potential.

The soil lies beneath the horizontal plane x, y with a vertical coordinate z, directed downward. Let q be the vertical water flux, θ the soil moisture, Ψ the suction head, and K the hydraulic conductivity. The two basic equations of one-dimensional flow are Darcy's law and continuity equation. The Darcy's law can be expressed as:

$$q = K\left(\frac{\partial\psi}{\partial z} + 1\right). \tag{4.5}$$

And, the continuity equation

$$\frac{\partial\theta}{\partial t} = \frac{\partial q}{\partial z}. \tag{4.6}$$

Elimination of q from the above two equations leads to the well-known Richards' equation for θ:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial\psi}{\partial z}\right) + \frac{\partial K}{\partial z} \tag{4.7}$$

or

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left(K\frac{\partial\psi}{\partial\theta}\cdot\frac{\partial\theta}{\partial z}\right)+\frac{\partial K}{\partial z}.$$

During the infiltration process into a soil of depth L, water moves into the soil through the soil surface at a rate that is determined by the initial and boundary physical conditions of the soil water. Thus, the soil water profiles are obtained by solving the above equation subject to the initial conditions in the soil profile:

$$\theta=\theta_n \quad t=0 \quad 0<z<L\,, \tag{4.8}$$

$$q=q_0 \quad 0<t<t_i \quad z=0\,, \quad \text{for } \theta(0,t)<\theta_s, \tag{4.9}$$

$$q=0 \quad t>t_i \quad z=0\,, \tag{4.10}$$

where $\theta_n \geq \theta_r$ is the constant, initial moisture content, q_0 is the given constant flux on the surface, t_i is the infiltration time.

If $\theta(0, t)$ reaches the saturated value θ_s for $t_p< t< t_i$, (4.8) is replaced by

$$\theta=\theta_s \quad t_p<t<t_i \quad z=0\,, \tag{4.11}$$

where t_p is defined as ponding time.

Surface boundary condition is given either in terms of prescribed soil-water content or soil-water pressure head. The subscript 0 refers to values at the soil surface at $z = 0$. The lower boundary condition at $z = L$ is similarly defined in terms of prescribed soil-water content or pressure head, or in terms of a prescribed flux.

In the derivation of (4.7), the soil is assumed to be uniform, homogeneous, and inert porous material in which Darcy's law describes the flow of water, and the effect on water movement on the air in the soil pores in assumed negligible.

Infiltration and redistribution of rain or irrigation water in soil involve vertical water movement, which can be described by Richards' equation. For cases of infiltration into soils of finite depth, two simple conditions at the lower boundary are given: (i) a water-table ($\psi = 0$), and (ii) an impermeable barrier ($\delta\psi/\delta z = 1$). With steady-state infiltration to a water-table, the soil-water profile is easily obtained by numerical integration of Richards' equation. In the field, the description of infiltration is highly complicated since the initial and boundary conditions are usually not constant while the soil characteristics may vary with time and space.

Generally, the $K(\theta)$ and $\psi(\theta)$ relationships needed to solve (4.7) are determined empirically. The solution of (4.7) associated $K(\theta)$ and $\psi(\theta)$ relationship and boundary and initial conditions (4.8–4.11) has been the subject of numerous studies aiming at obtaining approximate analytical expressions or numerical solution for $\theta(z, t)$, q_0, and θ_n.

Other Forms of Richard's Equation

The diffusion form of (4.6) for non-hysteric flow is obtained by introducing the soil-water diffusivity, $D = K/C$, where $C = \partial\theta/\partial\psi$ is the specific water capacity, as:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}(D\frac{\partial\theta}{\partial z}) + \frac{\partial K}{\partial z}. \tag{4.12}$$

The potential-based (ψ-based) form of Richards' equation is:

$$C_{\mathrm{w}}(\psi)\frac{\partial\psi}{\partial t} = \frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial\psi}{\partial z} + 1\right)\right], \tag{4.13}$$

where $C_{\mathrm{w}}(\psi) = \partial\theta/\partial\psi$ is defined as the water capacity function, and $K(\psi)$ is unsaturated hydraulic conductivity function.

Both θ- and ψ-based forms of Richards' equation are used in modeling because each form has specific advantages and disadvantages in numerical implementation. The θ-based form enables a fast solution in terms of computer time and conserves mass balance, but can not be used to simulate flow under saturated conditions. The ψ-based form is more suitable for variably-saturated soil (including fully saturated) conditions and spatially heterogeneous soils.

Approximations/Assumptions in Richards' Equation

Richards' equation suffers from the limitations that are pertinent to Darcy's law. Richards' equation makes assumptions in the physics of the flow that do not account for many complicating factors. These factors include the influence of air phase on the soil-water movement, the effects of soil heterogeneity, soil swelling, soil aggregation and soil instability, thermal effects, and hysteresis in soil–water relationships.

Practical boundary conditions may not comply with the idealized ones assumed in deriving infiltration equation and complicating factors often make Richards' model an inappropriate basis for computing soil-water flow. The effects of different factors are described below.

Effect of Soil-Air

Infiltration is a two process, with air being displaced by the infiltrating water. The effect of the air is not negligible in certain circumstances. There are two situations: First, water advancing in the pore network can leave behind isolated air-filled pores that are not connected with the main body of air. These air-filled pores change the soil hydraulic properties. Second, air may be swept in front of the wetting front, increasing the air pressure on the water menisci. This is important for bounded soil regions where the air displaced by the infiltrating water has no path for escape.

Soil Swelling

Richards' equation assumes soils to be simple inert porous material in which the water movement is unaffected by external loads. In swelling soils, consideration has to be given to the overburden pressure, which changes the soil–water relationships in the theoretical treatment of soil-water movement.

One consequence of swelling and shrinkage in natural soils is the formation of cracks that separate micropore regions of aggregates from macropore channels. There is then preferential flow of water through the macropores when they are full, but when they are empty the aggregates become isolated, with little water movement from one to another. Bypass flow down macropores around aggregates is thus an important aspect of flow during infiltration. Swelling and shrinkage in clay soils also give rise to temporal variations in soil hydraulic properties. Infiltration theory has not addressed this problem of soil instability.

Non-Darcian Flow

Deviation from Darcian behavior of water flow in soils can occur because of inertial effects and also because the soil water may not behave as a Newtonian fluid, as in soils of high colloid content. Darcy's law fails when the Reynolds number for the flow exceeds about one. Infiltration theory predicts very high flow velocities at early time, and infiltration theory based on Richards' equation must be incorrect. However, non-Darcian flow conditions lasted only for a very short time.

Horizontal Infiltration (Absorption) of Water from Cracks

Dry clay soils consist of relatively large natural aggregates (peds), which are separated from adjoining peds by vertical cracks. Along large pores or cracks in unsaturated soil, preferential movement of "free" water occurs. Vertical infiltration of water occurs at the soil surface into the upper surfaces of the peds. Water flowing into the cracks is absorbed horizontally into the peds. Water absorption from crack (horizontal infiltration) in each compartment can be described by the following equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[D\frac{\partial \theta}{\partial x}\right] \tag{4.14}$$

subject to the following boundary conditions:

$$x = 0 \quad \frac{\partial \theta}{\partial t} = 0 \quad t > T(\mathrm{c}),$$

$$x > x_t \frac{\partial \theta}{\partial t} = 0 \quad t > T(\mathrm{c}),$$

where D is the diffusivity, a function of moisture content (cm^2 d^{-1}), x is the distance from surface of infiltration (cm), θ is moisture content, T(c) is the time when flow into the cracks starts, x_t is the horizontal penetration of the wetting front at time t

Vertical Infiltration of Rain or Irrigation Water

General form of the equation of vertical infiltration of water through the soil aggregate can be written as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial H}{\partial z}\right), \tag{4.15}$$

where θ is water content, H is hydraulic head, z is distance, t is time, and K is conductivity. If the hydraulic head consists of pressure head and gravity head, and the gravity head is considered positive downward, then

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial \psi}{\partial z}\right) + \frac{\partial K}{\partial z}. \tag{4.16}$$

Flow of Water in a Heterogeneous Soil-Root System

Flow of water in a heterogeneous soil-root system can be described as (Feddes et al. 1978):

$$\frac{\partial h}{\partial t} = \frac{1}{C(h)} \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - \frac{S(h)}{C(h)}, \tag{4.17}$$

where h is the soil-water pressure head (cm), negative in unsaturated soil; t is the time (days); C is the differential moisture capacity, $\partial\theta/\partial h$, with θ being the volumetric soil-water content (cm^{-1}); Z is the vertical coordinate, with origin at the soil surface, directed positive upwards (cm); K is the hydraulic conductivity (cm day^{-1}); and S is the water uptake by roots (day^{-1}).

Feddes et al. (1978) described the sink term as:

$$S(h) = \alpha(h)\, S_{\max},$$

where $\alpha(h)$ is the prescribed function of soil-water pressure head and $S_{\max}$ is the maximum possible root extraction rate.

Darcian Flux or Flux Density and Flow Velocity

The Darcian flux or flux density is the volume of water passing through a unit cross-sectional area per unit time. Mathematically it is expressed as:

$$q = \frac{Q}{A}.$$

The flow is assumed to take place through the entire cross-sectional area. The dimension is volume per unit time per unit area (wrongly named as "length per unit time"). The flow velocity is given by the ratio of flux to volumetric soil-water content. Mathematically, it can be expressed as $v = q/\theta$.

4.2.3.8 Solutions of the Richards' Equation

(1) *Philip's solution*: Philip (1957a) presented a general solution for the Richards (1931) partial differential equation of soil-water movement. The Philip solution consists of an infinite series of power terms in increments of the square root of time, $t^{1/2}$:

$$x = \alpha_1 t^{1/2} + \alpha_2 t + \alpha_3 t^{3/2} + \cdots, \tag{4.18}$$

where x is the vertical ordinates and the co-efficients $\alpha_1, \alpha_2, \alpha_3, \ldots$ are functions of water content, θ.

This infinite series is not convenient for infiltration computations; however, it convergences rapidly. Consequently, by retaining only the first two terms, Philip (1957b) introduced the well-known Philip two-term algebraic infiltration equation,

$$I = S(t)^{1/2} + At. \tag{4.19}$$

And the related rate equation is:

$$\frac{di}{dt} = \frac{S}{2(t)^{1/2}} + A, \tag{4.20}$$

where S is the sorptivity.

The sorptivity S has a distinct physical meaning and takes into account the properties of the soil in terms of the hydraulic conductivity – moisture content characteristic $K(\theta)$, the moisture potential–moisture content characteristic $\psi(\theta)$, and the initial and final moisture contents θ_0 and θ.

The sorptivity S can be obtained either from horizontal infiltration experiments or by calculation from the diffusion coefficients vs. moisture content relationships. Philip (1958) defined sorptivity as:

$$S = [2K_0(h_c + h_0)]^{0.5}, \tag{4.21}$$

where K_0 is the final constant hydraulic conductivity, h_c is the capillary head at wetting front, h_0 is the constant water depth on soil surface.

Thus the equation defines sorptivity as a constant.

The practical determination of the coefficient A, in (4.20) can not be made independently of the determination of S. Philip (1969) remarked that a "best fit" of data over the whole t range will tend to give $A = K$.

(2) *Swartzendruber's solution*: Swartzendruber (1997) obtained two-term infiltration equation by integration from an exact solution of the one-dimensional downward Richards equation subject to the customary initial and boundary condition as:

$$I = St^{1/2} + K_0 t, \tag{4.22}$$

which is a form of the Philip's (1957b) two-term infiltration equation (eqn. 4.18).

By differentiating the above equation,

$$\frac{\mathrm{d}I}{\mathrm{d}t} = K_0 + \frac{S}{2t^{1/2}}, \tag{4.23}$$

where K_0 is the saturated hydraulic conductivity and S is the sorptivity.

Included in (4.18) are both zero and non-zero initial surface ponding.

(3) *Numerical solutions*: In recent years, efforts have been concentrated on seeking numerical solution of infiltration equations. Equations are solved using explicit or implicit methods. In the explicit method, a series of linearized independent equations are solved directly, while in the implicit method a system of linearized equations has to be solved. Numerical models are a reliable tool for predicting infiltration of water into soil.

4.2.3.9 Empirical Infiltration Equations

The process of infiltration can be described either in a quantitative way by solving the complete transport equation (Richards') with volumetric water content and depth as dependent variable, or by considering a relationship between cumulative infiltration and time expressed as a function of some empirical or physical infiltration parameters. As the latter approach is simple to operate, it is chosen in most of the field operations.

In case of infiltration process, normally we need to quantify infiltration rate and/or infiltration capacity, and cumulative infiltration over a period.

Horton's Equation

It is a three parameter infiltration model. Horton's infiltration equation may be written as (Horton 1939):

$$f(t) = f_c + (f_0 - f_c)e^{-\beta . t}, \tag{4.24}$$

where $f(t)$ is the infiltration rate at any time t(mm/h), $f_c$is the final constant infiltration rate (mm/h), f_0 is the initial infiltration rate at time zero (mm/h), t is the time (h), β is the empirical parameter, which should be determined experimentally for a particular soil (i.e., it is a best data-fit parameter).

Collis-George's Equation

Collis-George (1977) proposed an empirical equation, which satisfies the conditions that cumulative infiltration is proportional to (time)$^{1/2}$ at short times and reaches a steady-state infiltration rate at long times:

$$I = i_0(\tan hT)^{1/2} + Kt, \tag{4.25}$$

where I is the cumulative infiltration at time t, K is the infiltration rate at steady state, $I_0 = S(t_c)^{1/2}$, $T = t/t_c$. The sorptivity (S) and a time parameter t_c are soil properties determinable experimentally.

Green–Ampt Equation

The Green–Ampt equation is based on Darcy's law and the principle of conservation of mass for idealized conditions. The Green and Ampt equation in its simplest form can be written as (Green and Ampt 1911; Mein and Larson 1973):

$$f = -K_s \frac{dh}{dz} = -K_s \frac{h_f - h_0}{Z_f}, \tag{4.26}$$

where K_s is the saturated hydraulic conductivity, $\mathrm{d}h/\mathrm{d}z$ is the hydraulic gradient, h_f is the hydraulic head at the wetting front, h_0 is the hydraulic head at the soil surface, and Z_f is the depth of wetting front.

Assuming no ponding, $h_0 = 0$, thus,

$$f = -K_s \frac{h_f}{Z_f} = K_s \frac{\psi_f + Z_f}{Z_f}, \tag{4.27}$$

where ψ_f is the matric pressure at the wetting front.

The depth of wetting front is related to the cumulative amount of infiltrated water (F) by:

$$F = Z_f(\theta_s - \theta_i),$$

where θ_s is the saturated moisture content, θ_i is the initial moisture content (before irrigation began).

Rearranging the above equation for Z_f and substituting it in (4.27) yields infiltration equation:

$$\begin{aligned} f &= K_s + K_s \frac{\psi_f(\theta_s - \theta_i)}{F} \quad \text{for} \quad t > t_p \left[\mathrm{cm^3 s^{-1} cm^{-2}}\right], \\ f(t) &= P \quad \text{for} \quad t \leq t_p, \end{aligned} \tag{4.28}$$

where P is the rainfall rate (cm/h) and t_p is the time when water begin to pond on the surface (h).

Kostiakov Equation

Kostiakov (1932) proposed a simple two parameter empirical equation in the form of:

$$\begin{aligned} Y &= at^b, \\ I &= abt^{b-1}, \end{aligned} \tag{4.29}$$

where Y is the total infiltration depth in time t; t is the infiltration opportunity time; a, b are the soil parameters that depend on the soil and its physical condition; and I is the infiltration rate.

Modified Kostiakov Equation

The rate of the above-mentioned Kostiakov equation implies that infinite initial rate and the ultimate or final rate is zero. To remove this difficulty, another term was added to the above equation, which contains the basic infiltration rate (c). This modified equation is known as the Modified Kostiakov equation, which is as follows:

$$\begin{aligned} Y &= at^b + ct, \\ I &= abt^{b-1} + c. \end{aligned} \tag{4.30}$$

A disadvantage of this equation is that, values for three constants, a, b, and c, are difficult to obtain either from plotted infiltration data or from the least squares regression analysis. By combining and modifying the above equations, a third equation was developed known as "Branch equation," where the infiltration follows a power function until it reaches a constant value (basic infiltration rate), and after that it remains at that value.

Branch Equation

This equation is in the form of:

$$\begin{aligned} Y &= at^b \qquad t \leq t_{\mathrm{b}}, \\ I &= abt^{b-1}. \end{aligned} \tag{4.31}$$

and

$$\begin{aligned} Y &= at_{\mathrm{b}}^b + c(t - t_{\mathrm{b}}) \qquad t \geq t_{\mathrm{b}}, \\ I &= c, \end{aligned}$$

where t_{b} is the infiltration opportunity time when the basic infiltration rate (c) has been reached.

Most infiltration models assume the following:

- The soil is homogeneous
- Water moves vertically
- Moving water is liquid only
- Water movement is not affected by airflow in soil pores, temperature, and osmotic gradients

4.2.3.10 Measurement of Infiltration

Single Ring Infiltrometer

Single ring infiltrometer consists of a single metal cylinder that is driven partially into the soil (Fig. 4.5). The ring is filled with water and the rate at which the water

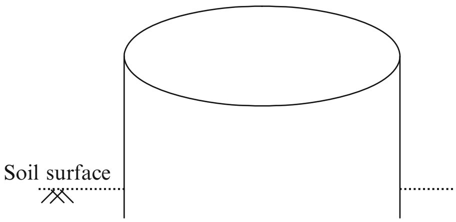


Fig. 4.5 Schematic of setting of single ring infiltrometer

moves into the soil is measured. This rate becomes constant when the saturated infiltration rate for the particular soil is reached.

It has been suggested that a diameter of at least 100 cm should be used for accurate results. The smaller the cylinder diameter, the higher the measurement error compared with the infiltration rate that would be measured with a ring of infinite diameter.

Another possible source of error occurs when driving the ring into the ground, as there can be a poor connection between the ring wall and the soil. This poor connection can cause a leakage of water along the ring wall and an over estimation of infiltration rate.

Operational Technique

There are two operational techniques used with the single ring (as well as double ring) infiltrometer for measuring infiltration rate: constant head and falling head techniques. In the constant head technique, the water level in the ring is maintained at a fixed level and the volume of water used to maintain this level is measured. In the falling head technique, the time taken for the water level to decrease certain amount is recorded. The record is taken normally at 1, 2, 5, 10, 20, 30, 60, 120, and 180 min from the start of the test, until a constant rate is reached. The data are then processed for graphical and analytical solutions for infiltration pattern (infiltration rate and cumulative infiltration).

Single-ring infiltrometers overestimate vertical infiltration rates. This is because the flow of water beneath the cylinder is not purely vertical and diverse laterally. The lateral divergence is due to sorption and capillary forces of the surrounding dry soil, and layers of reduced hydraulic conductivity below the ring. A number of techniques for overcoming this error have been developed. Double ring infiltrometers minimize such error.

Double Ring Infiltrometer

In double ring infiltrometer, two rings, inner and outer, are used (Fig. 4.6). Double ring infiltrometer minimizes the error associated with the single-ring method because the water level in the outer ring forces vertical infiltration of water in the

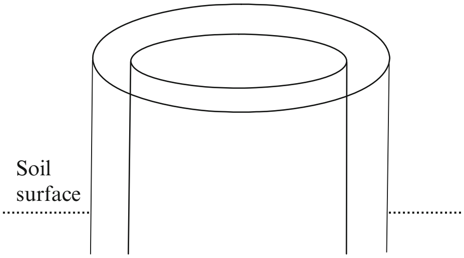


Fig. 4.6 Double ring infiltrometer

inner ring. The inner and outer cylinder diameter may be 30 and 45 cm respectively, or higher.

The constant head or falling head techniques are also used in double infiltrometer. In both techniques, the water level in the outer ring is maintained at a constant level to prevent leakage between rings and to force vertical infiltration from the inner ring.

In many cases, the falling head test is preferred since less water and time are required to complete a test.

Example on Infiltration Test Data Processing

Example 4.3. In an infiltration test, the following data were obtained:

Time from starting (min)	0	1	2	5	10	20	30	60	90	120
Depth of water level from ref. level (cm)	0	0.3	0.5	0.9	1.4	1.8	2	2.4	2.8	3.2

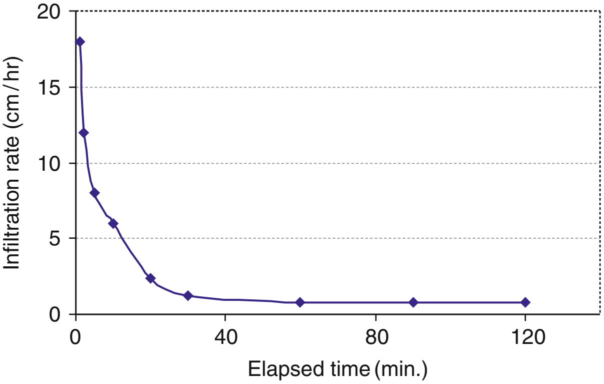
Plot the infiltration rate vs. time, and find out the basic infiltration rate.

Solution.

Time (min)	Cumulative drop in depth (cm)	Drop in depth for the period (cm)	Infiltration rate (cm/h)
0	0	0	–
1	0.3	0.3	18
2	0.5	0.2	12
5	0.9	0.4	8
10	1.4	0.5	6
20	1.8	0.4	2.4
30	2	0.2	1.2
60	2.4	0.4	0.8
90	2.8	0.4	0.8
120	3.2	0.4	0.8

Infiltration rate for a particular period = drop in depth in 1 h
For example, at 10-min period, infiltration rate $= [(1.4 - 0.9)\text{cm}/(10 - 5)\text{min}] \times 60 = 6$ cm/h

From the above calculation table, it is evident that the constant infiltration rate, or the basic infiltration rate = 0.8 cm/h (*Ans.*)
The graphical presentation of infiltration rate is given below:



4.2.4 Importance of Soil Physical Properties

4.2.4.1 Application of Principles of Soil Physical Properties to Field Problem

The principles of soil composition, particle size, bulk density, compaction, water movement can be directly applied to field situations and everyday problems. Issues about layering, root zone depth, top-dressing sand selection, etc. all involve the above principles. Making decisions when building a new facility or when managing an existing facility should take careful consideration of the physical aspects of soil.

Case 1: A Layer of Finer Material Over a Coarser Material

In some cases (e.g., new development sites, greens, and athletic fields), the fields are top-dressed with sand that are finer than those used in the original root zone mixture. After some years of top dressing with these finer sands plus the accumulation of some organic materials, a layer of fine top dressing sand mixed with organic matter develops at the soil surface. Because of the fineness of the sand, this layer retains a higher amount of water than the original root zone mixture. This is further aggravated by the high amount of organic matter in the layer. Thus, the upper layer stays too wet, and is poorly aerated. Thus, the layer is not well suited for good root development and the roots tend to stay close to the surface where they can get adequate oxygen. If the condition develops to the point that it becomes devoid of oxygen, black layer conditions can develop.

Case 2: A Layer of Coarser Sand Over a Finer Material

We may encounter the reverse problem with a layer of coarser sand over a finer material. This problem is less serious, but it is still a management problem. First, the coarser sand will likely have a low water holding capacity and will likely be droughty. This may cause difficulties in managing water at early growing stage until the crop develops an extensive root system. The higher saturated hydraulic conductivity and low cation exchange capacities, which are typical of coarse sands, will promote leaching of plant nutrients – particularly nitrogen and potassium. A third problem associated with coarse sands placed over finer materials is the need for drainage. Since the coarse sand will have a relatively high infiltration rate, water will rapidly enter this layer until it becomes saturated. When the rainfall or irrigation is over, provisions must be made to allow the gravitational water to escape. This may require the installation of a subsurface drainage system in some instances. In some cases, the permeability of the underlying soil may be sufficient to handle the drainage water in a reasonable amount of time. In either case, suitable provision must be made to prevent the water remaining in the coarse layer for an extended period of time. Otherwise, it will result in anaerobic soil conditions.

To avoid the problems mentioned earlier, sand with the same particle size distribution as that used to construct the area being top dressed is ideal. If an exact match can not be found, then one should select such material which is slightly coarser than the original. This will avoid the formation of an excessively wet and poorly aerated layer near the surface.

4.2.4.2 Relation of Irrigation Scheduling and Drainage to Physical Properties of Soil

Irrigation scheduling is directly related to the physical properties of soil. A sandy soil with a high infiltration rate can accept water rapidly; however, it will hold only a relatively small amount prior to drainage. Clay texture soils are the opposite and only allow water to enter them very slowly; however, they hold a large amount of water. Thus, the physical properties of a soil control both the rate at which water may be applied and the total amount of water to be applied.

In connection to drainage, it is important to realize that large pores in the coarse textured soil can conduct more water more rapidly than fine pores. In addition, removing water from large pores is easier and requires less energy than removing water from smaller pores of fine textured soil.

4.3 Chemical Properties of Soil

In addition to physical properties, soils have unique chemical properties as well. The main chemical properties of soil are pH, CEC, salinity, carbon to nitrogen ratio (C/N ratio), etc.

4.3.1 Soil pH

4.3.1.1 Definition and Expression of Soil pH

Soil pH is a measure of the acidity or alkalinity of a soil. Soil pH influences many facets of crop production and soil chemistry, including availabilities of plant nutrients, toxic substances, activities and nature of microbial populations, solubility of heavy metals, and activities of certain pesticides.

The pH is defined as the negative logarithm of the hydrogen ion (H^+) concentration. When water is ionized to H^+ and OH^- (a neutral solution), both H^+ and OH^- ions are in equal concentrations of 0.0000001 moles per liter.

$HOH \leftrightarrow H^+ + OH^-$

$[H^+] = [OH^-] = 1 \times 10^{-7}$mol/L. The H^+ ion and OH^- concentrations in water are very small.

The pH scale has been devised for conveniently expressing these small concentrations by expressing $pH = Log\{1/[H^+]\}$. When pH is 7.0, it is neutral, when $pH < 7.0$, it is acidic, and when $pH > 7.0$, it is alkaline.

When the hydrogen concentration is greater, such as 0.0001 mol/L, the pH is 4; when it is smaller, such as 0.00000001, the pH is 8. Logarithmic scale means that a 1-unit drop in pH is a 10-fold increase in acidity. So a pH of 5 is ten times more acidic than a pH of 6 and 100 times more acidic than a pH of 7.

4.3.1.2 Causes for Acid Soils

The pH of a soil is dependent on the parent material, the climate, the native vegetation, the cropping history (for agricultural soils), and the fertilizer or liming practices.

The pH range for most mineral soils would be from 5.5 to 7.5, and in general, it is the optimal pH range.

4.3.1.3 Sources of H^+ Ions in the Soil

The main sources of H^+ ions in the soil are as follows:

1. Dissociation of carbonic acid, which forms readily in soils when CO_2 is present
2. Organic acids formed during the decomposition of organic matter
3. The burning of coal in electrical power plants releases sulfur to the atmosphere, which is added to soils during precipitation as sulfuric acid, and fertilizers containing sulfur, which adds H^+
4. The conversion of NH_4^+ to NO_3^- releases H^+ during the nitrogen cycle or when nitrogen fertilizers are added to soils

$pH < 4.0$ indicates that the soil contains free acids probably as a result of sulfide oxidation.

$pH < 5.5$ indicates that the soil's exchange complex is dominated by Al.

$pH < 7.8$ indicates that the soil pH is controlled by a range of factors.

$pH > 7.8$ indicates that the soil contains $CaCO_3$.

4.3.1.4 Soil pH Determination

One method to determine soil pH is by using a pH indicator dye (indicator dye pH kit or Poly D). It is easy to use and gives a suitable pH value for most soils. The indicator dye is added to the soil in a pot until it is saturated. The solution is stirred using a small spatula. The solution will change color depending on the soil pH. The solution color is compared with a color card that has been calibrated to various pH readings.

A more accurate determination can be made using a pH meter and glass electrode. The electrical conductance of the solution is measured using the meter. The conductance is correlated in the machine to pH values, which are read directly.

pH Determination Using pH Meter

There are three main internationally accepted methods available for measuring soil pH. All of them rely on shaking (or stirring) soil with a solution for 1–2 h and then determining the pH of the resultant soil slurry. The working method is given below:

1. Weigh out 10 g of soil into labeled 100-ml plastic (polypropylene) tubes
2. Add one of the following three solutions:
   (a) 50 ml of distilled water. (This is the simplest method and normally OK for most soils. It does not remove H^+ from the exchange sites and is not very good for soils having high salt content)
   (b) 50 ml of 1 M KCl (used to mask differences in soils's salt content). Useful if determining exchangeable cations as both cations and pH can be done on the same sample. It does displace H+ from the soil's cation exchange sites, so the result are usually slightly lower than those obtained with methods (a) and (c).
   (c) 50 ml of 0.01 M $CaCl_2$. This is an intermediate between methods (a) and (b) and masks small differences in the soil's salt content.
3. Shake for 1 h at room temperature (25°C)
4. Let the soil settle for a few minutes (e.g., 3 min) and measure the pH after a two point calibration (pH 4 and pH 7) of the pH meter.

In determining pH, field moist soil (store at 5°C) should preferably be used.

4.3.2 *Soil Cation Exchange*

4.3.2.1 Concept

A cation is a positively charged ion. Most nutrients are cations, such as Ca^{2+}, Mg^{2+}, K^+, NH^{4+}, Zn^{2+}, Cu^{2+}, and Mn^{2+}. These cations are in the soil solution and are in dynamic equilibrium with the cations adsorbed on the surface of clay and organic matter.

The soil cation exchange is the interchange between a cation in solution and another cation on the surface of any negatively charged material such as clay or organic matter.

4.3.2.2 Factors Affecting Cation Exchange

Cation exchange is influenced by the following:

1. Strength of adsorption
2. The relative concentration of cations in the soil solution.

Thus, at any one time, the quantity of ions on the exchange compared with what is in the soil solution is determined by the kind of ions present and the quantity in the soil.

4.3.2.3 Cation Exchange Capacity

CEC is the ability of the soil to hold onto nutrients and prevent them from leaching beyond the roots. The CEC of a soil is simply a measure of the quantity of sites on soil surfaces that can retain positively charged ions by electrostatic forces. Cations retained electrostatically are easily exchangeable with other cations in the soil solution and are thus readily available for plant uptake. Thus, CEC is important for maintaining adequate quantities of plant available calcium (Ca^{++}), magnesium (M^{++}), and potassium (K^+) in soils. Other cations include Al^{+++} (when $pH < 5.5$), Na^+, and H^+.

The CEC is dependent upon the amount of organic matter (OM) and clay in soils and on the types of clay. In general, the higher OM and clay content, the higher the CEC. The more CEC a soil has, the more likely the soil will have a higher fertility level. When combined with other measures of soil fertility, CEC is a good indicator of soil quality and productivity.

4.3.2.4 Expression of Cation Exchange

CEC can be expressed in two ways:

1. The number of cation adsorption sites per unit weight of soil
2. The total exchangeable cations that a soil can adsorb

Table 4.3 Milliequivalent weight of some cations

Element	Valence	Atomic weight (g)	Meq wt. (g)
K+	1	39	0.039
Na+	1	23	0.023
Ca++	2	40	0.020
Mg++	2	24	0.012

Soil CEC is normally expressed in units of charge per weight of soil. Two different, but numerically equivalent sets of units are used: meq/100 g (milliequivalents of element per 100 g of dry soil) or cmolc/kg (centimoles of charge per kilogram of dry soil). The unit of milliequivalents (meq) per 100 g of oven dry soil is used to better reflect it. It is the charge in the soil that determines how many cations can be attracted. The equivalent weight of an element is the molecular or atomic wt (g) ÷ valence; or charges per milliequivalent (meq). One meq weight of CEC has 6.02×10^{20} adsorption sites. Cation exchange sites are found primarily on clay and OM surfaces.

Milliequivalent weight (meq wt.) of common cation elements are given in Table 4.3:

Normal CEC ranges in soils would be from <1 meq/100 g for sandy soils low in OM to >25 meq/100 g for soils high in certain types of clay or OM. Soil OM develops a greater CEC at near-neutral pH than under acidic conditions. Additions of an organic material will likely increase a soil's CEC. Soil CEC may decrease with time through acidification and OM decomposition.

4.3.2.5 Predicting CEC

CEC estimates can be made based on the texture and amount of organic matter of the soil.

1. Estimation based on texture:

	Texture				
	Sand	LS to SL	Loam	Clay loam	Clay
CEC meq/100g	0–3	3–10	10–15	10–30	>30

LS = loamy sand, SL = sandy loam

$$\text{CEC} = (\%\text{OM} \times 200/100) + (\%\ \text{Clay} \times 50/100) \qquad (4.32)$$

2. Calculation of CEC with % clay and % OM.

The above formula assumes average CEC for % OM = 200 meq/100 g, and the average CEC for % clay = 50 meq/100 g.

Therefore, from soil data: soil with 2% OM and 10% clay,

$$\mathrm{CEC} = (200 \times 2/100) + (50 \times 1/100) = (4 + 5) = 9\mathrm{meq}/100\,\mathrm{g}$$

4.4 Soil Hydraulic Properties

Over the years, numerous in situ and laboratory methods have been developed to determine soil hydraulic properties. Although in situ methods generate results that are more representative of field conditions, laboratory experiments offer more flexibility in initial and boundary conditions. Soil water functions are also more accurately and more conveniently measured in laboratory; and measurements are made faster across a wide range of soil water content.

4.4.1 Importance of Soil Hydraulic Properties

Knowledge of soil hydraulic properties is essential to allow application of existing soil physical theory to practical land management issues. Dynamics of unsaturated soil systems can be described by various differential equations derived from the combination of Darcy's law and conservation of mass principle (as described earlier). Application of such equations under various boundary and initial conditions require knowledge of volumetric water content in soil (θ), soil water suction (ψ), the rate at which water flows in the soil (k), soil water diffusivity (D), change in soil water content per unit change in suction (C), and the relationships among them. Soil hydraulic properties such as the movement of water to plant roots, the flow of water to drains and wells, water holding capacity, moisture release properties, solute transport, and the evaporation of water from the soil are essentially required for developing irrigation scheduling for maximizing water use efficiency.

Scientific management of irrigation system requires a thorough understanding of the hydraulic and drainage characteristics of soil of any command area. This facilitates prevention of water logging and salinization through adoption of preventive measures at proper time.

4.4.2 Determination of Different Soil-Water Constants

4.4.2.1 Water Holding Capacity/Water Retention Capacity/Field Capacity

The term "water holding capacity," "water retention capacity," and "field capacity" are interchangeably used. It is the amount of water held in the soil after the excess gravitational water has drained away and after the rate of downward movement of water has materially decreased. Some descriptions regarding water holding capacity are given earlier. The size, shape, and arrangement of the soil particles and the associated voids or pores (i.e., soil texture and structure) determine the ability of a soil to retain water. It is also influenced by organic content and over-burden pressure or compaction (if any). Sandy soils consist mainly of large mineral particles with very small percentages of clay, silt, and organic matter. In sandy soils, there are many large pores than in clayey soils. But the total volume of pores in sandy soils is significantly smaller than in clayey soils (30–40% for sandy soils when compared with 40–55% for clayey soils). As a result, much less water can be stored in sandy soil than in the clayey soil. In addition, a significant number of the pores in sandy soils are large enough to drain within the first 24 h of saturation due to gravity and this portion of water is lost from the system before plants can use it.

As the field capacity is influenced by many factors, it is not precisely a constant. But in practice, it is considered as constant for a particular soil type, and the upper limit of soil moisture capacity in an unsaturated soil. A thermodynamic definition of field capacity for the upper limit was proposed by Colman (1947) to be at −33 kPa. Since then, the moisture content at −33 kPa has been used extensively as field capacity or field capacity moisture content. But for many soils, the moisture content after free (gravity) drainage (i.e., field capacity and the moisture at −33 kPa) showed considerable deviation (Riverand Shipp 1978; Casse and Nielsen 1986; Sinclair et al. 1998; Ali and Turral 2001).

Determination of Water Holding Capacity

Water holding capacity can be determined following field plot technique, from small container/pot, and laboratory technique.

(a) *From field plot*

In this method, a representative section from the field is selected, from which a plot of about 3 × 3 m^2 is bounded by 30-cm height bund/ridge. The area is made free from weed, if any. Water is added to the plot sufficiently enough to saturate the soil column (10–25 cm, depending on the initial soil moisture, soil type, and soil depth considered). A buffer zone of about 0.5–1.0 m surrounding the bund may be created to force the movement of infiltrated water toward downward. Water of same depth is also added in the buffer zone. When the ponded water at the soil surface is close to disappearance, the plot is covered by polythene to retard evaporation loss.

After the disappearance of ponded water, the plot is allowed to drain out the free or drainable water. It may require 1∼3 days depending on the soil type (1 day for sandy soil, 2 days for loamy soil, and 3 days for heavy clay soil). The water content in the soil column can be monitored by time domain reflectrometer (TDR) or neutron moisture meter (through inserting the aluminum tube previously).

After free drainage, the moisture reading by the instruments would be constant. Anyway, ensuring the cease of free drainage, the moisture content can be determined by previously calibrated TDR or neutron moisture meter, or soil sample can be collected through core sampler and determined through gravimetric procedure. For determination of moisture in weight basis, samples can be collected using the auger. Detail measurement procedure using TDR, neutron moisture meter, and gravimetric method are described in a later section. The moisture content of the samples represents the “water holding capacity” or “field capacity” of that field-soil.

(b) *From container/pot sample*

In this approach, a medium size container (5∼15 l capacity, metallic or nonmetallic) is taken and a provision is made to drain out the water from the container (by making a hole at the bottom side). Representative field-soil (as a monolith or disturbed loose soil) is taken into the container upto 80% of its volume and compaction is done (if necessary), so that it closely resembles the field condition. Water is added at the top of the container until water is appeared at the drainage outlet. Having small ponded water at the top, the container is covered with polythene to prevent evaporation. Observation is made to confirm whether the drainage stops or not. When no more water is appeared at the outlet, the soil-water is equilibrated with the gravity force. The soil-water content of the container-soil represents the water holding capacity or field capacity.

For volume percent moisture determination, the volume of the soil is recorded. The container is weighed with soil, and then without soil. The soil is then put into oven at 105°C for dryness until constant weight of the soil sample is reached. Then it is weighed and moisture content is determined.

(c) *Laboratory technique*

Principle: In this technique, the soil sample is collected from the field by core sampler and is subjected to saturation in saturated sand, and the moisture content is determined by gravimetric method.

Detail method: In this method, sampling of natural field soil (undisturbed) is done with the core sampler. Care is taken to avoid compression within the core soil. One of its end is wrapped with nylon cloth. Fine-graded sand is saturated in a tray or other type of container. The core samples are then put on the saturated sand with a slight twist. Water is added to the sand when the water drops below the top surface (to be monitored after 6 and 12 h). The soil of the sample will abstract water from the saturated sand by capillary rise. If the core height is 6 cm, then the average tension at which the water contains in the core sample is 3 cm. Several drops of water are to be applied on the top of the core sample for complete saturation (if any dryness). Depending on the soil type, a 6-cm core will be normally saturated within 24∼36 h. The samples are then taken from the container, wiped by dry cloth or tissue, and weighed. Then the samples are placed on an oven for dryness at 105°C until constant weight is reached. Then the moisture content is determined by the following equation:

$$\begin{aligned}&\text{Moisture content (\% vol.)}\\&\quad=100\times(\text{volume of water in soil}/\text{volume of soil})\\&\quad=100\times(\text{wt. of soil after saturation}-\text{wt. of soil after oven-dry})/\text{volume of core}\end{aligned}$$

4.4.2.2 Saturation Capacity/Maximum Water Holding Capacity

Similar to the process of determining water holding capacity, when the ponded water just disappears from the surface, the soil sample should be collected and moisture should be determined (no gravity drainage is allowed from the soil). This moisture content represents the saturation capacity of the soil.

4.4.2.3 Permanent Wilting Point Soil Moisture

Most plants wilt permanently (not regains its original activities) or die when soil moisture tension reaches to 15 bars. Normally, soil moisture content at 15 bar suction (pF of 4.2) is considered as the permanent wilting point moisture content *or* permanent wilting coefficient. The moisture content at this suction is determined using pressure plat apparatus. Details of this technique are described under "*soil moisture characteristic*" section. Moisture content at permanent wilting point varies with soil texture. Fine textured soils retain higher amount of water (~26–32% by volume) than the coarse textured soils (10–15% by volume) at permanent wilting point.

4.4.3 Measurement of Soil Water

4.4.3.1 Concept, Factors Affecting Soil-Water and Measurement Approaches

Soil-Water Content

Water content of a soil specimen is defined as the amount of water that is lost from the soil upon drying at 105°C, expressed either as the weight of water per unit of dry soil, or as the volume of water per unit volume of soil in bulk.

Factors Affecting Soil Water

The amount of water that is retained in unit volume of soil depends on various factors:

- Size and distribution of soil particles (texture)
- Pore space and their orientation
- Organic matter content
- Soil structure
- Soil temperature
- Compaction/over-burden pressure

Soil Texture

Total pore space in fine textured soils is higher (and also higher total surface area) than that of coarse textured soils, and hence more water is retained both at field capacity and at 15 bar tension. Effect of soil texture on water holding capacity has been described at an earlier section.

Soil Structure

Soil structure and texture together influence water retaining capacity.

Pore Space

Among the total pore, macro-pores hold water in the soil. Arrangement of the pores in the soil also influences the water retention.

Overburden Pressure or Compaction

Compaction or overburden pressure reduces the pore spaces and disrupt their arrangement, and thus influences on water retention.

Soil Water Measurement

A key component of good on-farm irrigation water management is the routine monitoring and measurement of soil water. It helps to avoid economic losses due to effect of under-irrigation and over-irrigation on crop yield and quality, waste of water and energy, and leaching of nutrients and agro-chemicals into surface and groundwater.

Techniques for measuring the soil moisture can be grouped into the following two categories:

(a) Direct measurement
(b) Indirect measurement

Under category (a), gravimetric or thermo-gravimetric procedure is the only one technique. But under category (b), several approaches are available. They measure some physical, chemical, electrical, thermal, acoustic, or cohesive property of the soil; or sensing unit that is altered by changes in soil moisture, or measure moisture potential directly. Most of these techniques require locating a sensor of some type. The sensor may permit to remain in situ. Some methods merely require the sensor at or near the surface with no disruption. Radio frequency, acoustic, and some thermal techniques have this advantage. The indirect measurement category includes the following:

1. Radiological method – Neutron scattering, gamma attenuation technique (e.g., using neutron moisture meter)
2. Electromagnetic method – Time domain reflectrometry (TDR), TDR FM, Diviner
3. Tensiometry method – using tensiometer
4. Psychrometer method

4.4.3.2 Gravimetric Moisture Determination

Principle of the Method

Gravimetric technique requires the removal of soil from the field and conveyed to a laboratory for weighing, and removal of soil moisture by heating in an oven.

General Considerations

Now-a-days, a wide range of sampling devices ranging from manual sampler (auger, core) upto power driven sampling tubes is commonly available. Collection and transport of samples have been simplified by the use of plastic bag or liners. Soil sampling can be done using auger (for weight basis determination) or core (for both volume and weight basis determination). The weight basis moisture percentage can be converted to volume basis moisture by multiplying it with the soil bulk density.

In case of auger sampling, the soil can be mixed thoroughly for the entire depth of sampling, or within the selected depth. For drying, 100–200 gm soil is desirable.

In case of core sampling, several aspects should be taken into account:

- The higher the core diameter, the lower the compaction effect during sampling, and vise versa. So proper and practical size core should be used (not less than 5 cm in diameter).
- The higher the core height, the greater the chance of compaction effect, and vise versa. So it is not wise to use core height greater than 10 cm.
- The roughness (or smoothness) of the inner surface of the core contributes to increase or decrease in compaction effect. So, the inner surface should be as smooth as possible. The smoothness of the surface can be increased by oiling with lubricant.

- Sharpness of the driving edge of the core contributes to increase or decrease in compaction effect. So, the edge should be sharp as possible to reduce the compaction effect.

Detail Systematic Working Method

1. Select an appropriate tool for soil sampling (e.g., auger, sampling core, or power driven sampler).
2. Collect soil from the representative location of the field upto required depth, preferably having several replications.
3. Wrap the sample with polythene and keep in a cool, closed box (such as ice box) to prevent moisture loss by evaporation. For methods other than the core sampler, mix the collected soil (as a whole or depth-wise) and take about 100 gm soil for each depth.
4. Transport the samples to laboratory and weigh in a digital balance (having 2–3 decimal points). In case of loose sample (other than core), weigh a steel or aluminum pot/plate before putting soil on the plate.

For core sample, after taking the initial weight of the core sample, remove the soils from the core and put it in a pot before placing it on an oven.

5. Keep sample in oven for drying at 105°C until the weight of the sample becomes constant (normally 24∼48 h).

As a trial, weigh the sample with plate after 24 h and record it. Reweigh the sample at 36 h and compare it with the previous weight. If the difference is not negligible, repeat the process until the weight does not change. Cool the samples at room temperature before weighing.

6. In case of core samples, record the height and inner diameter of the core for determining soil (core) volume.
7. Determine the moisture content using the following formulae:

$$\text{Moisture content, \%wt} = 100 \times (\text{wt. of water lost from the sample/wt: of oven-dry soil})$$

$$\text{Moisture content, \%vol.} = 100 \times (\text{volume of water lost from the sample/volume of soil})$$

$$\text{Moisture content, \%vol.} = (\text{Moisture content, \%wt.}) \times \text{bulk density of the same soil}$$

Then, average the moisture content over location, sampling depth, or root zone depth, as required. For convenience, data recording and calculation sheet are given below (Tables 4.4 and 4.5).

Instead of conventional drying oven, soil samples can be dried in microwave oven. In that case, drying period will be different, normally 20–30 min. Samples

Table 4.4 Calculation sheet for determination of moisture sampled with core sampler

Sl. no.	Wt. of wet soil + core (gm) (1)	Wt. of oven-dry soil + core (gm) (2)	Core volume			Actual soil vol. (cm^3)[a] (4)	Wt. of soil moisture (gm) (5) = (1)–(2)	% moisture (by vol.)[b] (6) = (5)%(4)
			Height, h(cm)	Dia, d(cm)	Vol. $= \pi d^2 h/4$ (3)			
1	98	62	6	5	117.8	117.8	36	30.6
2	102	60	5.5	5.1	12.4	112.4	42	37.4

[a] If the soil volume is less than the core volume (somehow some soil is dropped out), then the volume should be estimated by filling with sand, and the sand should be poured in small calibrated volumetric cylinder; and the volume should be deducted from the core volume [i.e., (4) = (3)–volume of lost soil]

[b] Density of water is assumed as 1 gm/cm^3

Table 4.5 Calculation sheet for determination of moisture sampled by auger

Sl. no. / sample ID	Wt. of wet soil and container (gm) (1)	Wt. of oven-dry soil and container (gm) (2)	Wt. of container (gm) (3)	Wt. of soil water (gm) (4) = (1)–(2)	Wt. of dry soil (gm) (5) = (2)–(3)	% moisture (wt. basis) (6) = 100 × (4)%(5)
1	105	85	25	20	60	33.3
2	95	82	21	13	61	21.3

should be weighed and reweighed for constant weight in the same manner as that of conventional oven-dry method.

Advantages of Gravimetric Method

1. The direct and most reliable method
2. Requires simple equipments, and the equipments are not so expensive, thus affordable by various categories of users
3. Requires less expertise, and thus usable by farmers
4. With the use of core sampler (known internal diameter and height), both bulk density and moisture percentage (in volume basis) can be determined with one set of sample
5. No radiation hazard

Disadvantages

1. Compaction during core sampling may cause error in bulk density and volumetric moisture content, if the edge of the core is not sharpened.
2. For loose, upper-layer soil (especially after plowing and at the initial stage of the crop), core sampling is problematic and estimation of bulk density may be erroneous.

3. Destructive sampling is required, thus not possible of second time sampling at the same place.
4. When the crop covers the field and root system develops, sampling hampers the crop.
5. Time consuming and labor intensive
6. Difficult in stony or rocky soil

4.4.3.3 Radiological Method

In this method two approaches are used:

(a) Neutron scattering
(b) Gamma attenuation

Neutron Scattering Technique

Principle

The neutron source emits (yields) a huge neutron per second. The hydrogen in soil-water thermalizes (slow down) the fast neutrons and the slow neutron comes back near the source, which is detected (counted) by a detector placed above the source. There is a direct relationship between the number of slow neutron coming back and the amount of hydrogen present in soil. An electronic processor converts this information into amount of water.

Theory of Radiation

Every element is composed of an atom having unique structure. The atom consists of electron, proton, and neutron. The proton and neutron are clustered together in the nucleus, and the electron orbits the nucleus. Proton carries a positive charge and has a mass of one. Neutron has a neutral charge and also has a mass of one. Electron carries a negative charge and has negligible mass. Since protons and neutrons are grouped together in the nucleus, the mass of an atom is concentrated in the nucleus. An atom is normally electrically neutral because the positive charge of proton cancels out the negative charge of electron.

In general, a radioactive material (e.g., Americium-241) is compressed into a pellet with a nonradioactive material (e.g., Beryllium). This mixture of radioactive and nonradioactive material causes an interaction that results in a neutron in the nonradioactive nucleus to be emitted. This emission entails a large energy transfer, causing the stable neutron to become a form of ionizing radiation.

Different types of radioactive sources produce the following types of radiation:

- Neutrons
- Gamma rays (Photons)

- Alpha particles
- Beta particles

Neutrons have no charge and are very penetrating. Neutron radiation allows measurement of the hydrogen (moisture) content in a material because the neutrons are slowed by collisions with materials containing hydrogen atoms (e.g., polyethylene, water).

Gamma radiation is electromagnetic radiation. It has no mass, zero electrical charge and travel at the speed of light. Gamma rays are energetic and penetrating. Dense materials (e.g., cadmium, lead) provide the best shielding against gamma radiation. Alpha and beta particles are easily controllable (i.e., by stainless steel, paper sheet) and less penetrating capacity. Available moisture measuring nuclear instruments include CPN HYDROBROBE (CPN – Instrotek) (Fig. 4.7), TROXLER (Troxler Inc.), ICT International, etc.

Fig. 4.7 View of a CPN Hydroprobe (*Courtesy*: CPN – Instrotek)

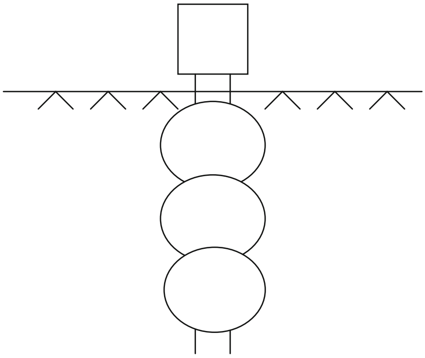


Fig. 4.8 Schematic of placement of neutron moisture meter on the top of access tube and radius of sphere (measurement) at different settings of the probe

The radius of measurement (Fig. 4.8) is a function of moisture content, and decreases with increasing moisture content. The relationship between radius of measurement and the moisture content can be expressed as (Adapted from Troxler Inc., 1996):

$$r = 280 - 2.7\theta, \quad 10 < \theta < 60, \tag{4.33}$$

where r is the radius of measurement (mm) and θ is the moisture content (% volume).

From the equation, it is observed that when soil moisture content (θ) is 18% (by vol.), the r is about 23 cm; and when θ is 44% (by vol.), the r is 16 cm.

Radiological Terminologies

Radioactivity. This is the spontaneous breakdown of unstable nuclei with the resulting emission of radiation. The SI unit of radiation is "Bequeral". One "Bequeral" is equal to one disintegration per second. Other unit of radiation is "Curie" (Ci). One "Curie" is defined as 3.7×10^{10} disintegrations of nuclei per second. One milli Curie is equal to 1/1,000 of a Curie.

Fast neutron. These neutrons are high energetic neutrons emitted from the radioactive source. It moves with the same velocity of light.

Thermalize neutron. "To thermalize" means that fast neutrons (that are emitted by the source) are slowed to a velocity where further collisions with hydrogen or other molecules will not slow the neutrons any more. Generally, the larger the element's atomic weight, the more collisions are required to slow the neutron. It takes about 19 collisions with hydrogen to thermalize a neutron.

Neutron absorbing elements. There are some elements that absorb neutrons into their nucleus. These include cadmium, boron, chlorine, manganese, titanium, uranium, iron, potassium, nitrogen, etc. (chronologically from higher to lower absorbing probability). Among these, cadmium, boron, and chlorine are typical problem elements. Organic matter in soil also affects moisture reading.

Radius of measurement or sphere of measurement. The radius of measurement is the distance through which about 98% of the counted thermalized neutrons pass before reaching the detector.

Half-life. The radioactivities of an isotope decrease or decay with time. Half-life of a radioactive material is the time required for 50% of a radioactive isotope to decay. Half life of the neutron or gamma sources that are normally used in neutron moisture meter are greater than 400 years. Therefore, the strength of the source will not significantly vary over the life of the instrument. But failure of other electronic systems may lead to failure/malfunctioning of the instrument.

Radiation absorption dose. The unit of radiation absorption dose is "RAD," which is equivalent to 0.01 joules/kg (100 ergs/gm) in any medium. To account for the effect of various types of radiation on biological tissue, the unit "rem" is used. One "rem" is equal to exposure of 0.1 RAD neutron radiation.

Limits of radiation exposure. Limits are set by appropriate authority or government. Generally, the occupational exposure limits are 1,250 millirems (mREM) in any calendar quarter for a maximum of 5,000 mREM in any 1 year. Exposure limit in many countries in the world including USA is 5,000 mREM.

The authorized users should be monitored using personal dosimeters. The most common types of dosimeters are "film badge" and "TLD badge." The "TLD badge" can measure both gamma and neutron radiations. "Film badges" are not suitable for measuring neutrons.

Working Procedure

Measurement of soil moisture with this technique (by neutron moisture meter) requires several steps, which are as follows:

1. Installation of access tube in the soil
2. Setting/placement of stopper in the inserting cable
3. Calibration of the instrument with the field soil (if needed)
4. Taking a reading
5. Analyzing the data

Installation of access tube. Access tubes may be aluminum, steel, or polyethelene pipe. Aluminum provides the best access tube. It absorbs very few thermal neutrons and is durable in the field. The length of access tube may be 1–3 m.

An access hole is drilled by an auger. An access hole needs to provide an exact fit for the tube and must be clear along the sides for easy installation. Voids along the side will bias reading, high when filled with water and low when filled with air. The access tube must be sealed at the bottom to prevent water seepage in the tube. This will prevent damage to the probe and erroneous readings. Sufficient length of tube (10–15 cm) should be kept above the ground to prevent water from entering the tube. A suitable size rubber stopper or metallic lead should be placed on the top of the tube (when not in use) to maintain the tube clean and dry.

Setting stopper at the inserting cable. Cable stops (stopper) provide a convenient method to locate an exact depth of measurement. Stoppers are fixed in the inserting (access) cable of the probe (radiation source) according to the desired interval of moisture reading (e.g., 10, 15 or 20 cm) upto the maximum depth of the access tube. The stoppers may be made of rubber or metallic element.

Length of 1st cable stop = height of access tube top above ground + height of the source from the bottom of the shield probe + desired depth of first measurement from the soil surface.

Then, the subsequent stoppers should be placed above the first stopper, according to the selected interval (normally fixed interval, for convenience).

Calibration with field soil. Field soils may contain some chemically bound hydrogen or neutron absorbing elements (described earlier), which makes it necessary to change the factory calibration. To calibrate the gauge to field soils, gauge readings are compared with gravimetric moisture contents. Data points should be taken at both dry and wet ends. An ideal calibration should consist of multiple reading (but at least two) at various moisture levels. Count ratio corresponding to each moisture content (% vol.) is recorded. Data pairs of instrumental count ratio vs. gravimetric moisture content are inserted into the machine. In some cases, adjustment/resetting the slope is sufficient for new calibration.

Taking a measurement/reading. The unit of the measurement is selected among the options (% volume, Kg/m^3, mm/m, Ibs/ft^3, count ratio, etc.). Measurement time (i.e., count time) is selected (15 s, 30 s, 1 min). The accuracy of the measurement increases with the count time. A standard reading of the instrument is taken by placing the probe on the access tube to check the stability of the instrument. If it is OK, then the neutron source (probe) is inserted to the desired depth through the access tube by cable stop. Then the "START" button is pushed for reading. The moisture reading becomes visible on the screen within the preselected time (15 s, 30 s, 1 min, etc.). The probe is then inserted to the next desired depth and reading is taken in the same way.

The recent models of neutron moisture meters are capable of storing data depthwise for multiple projects. These data can be transported to computer and get printed.

Accuracy of neutron moisture meter reading. The accuracy of neutron moisture meter in estimating soil-water content (and thereby the depletion) is usually affected by many factors including probe calibration, length of count interval, and spatial heterogeneity of soil water. In addition, various soil properties other than soil moisture produce a cumulative effect on the count rate and probe calibration. The impact of soil hydrogen in forms other than free water, neutron-absorbing elements, soil density, soil texture, and temperature effect was noted by Risinger (1984), who consequently recommended development of a calibration equation for each 30 cm depth in the soil profile to a 1.5 m depth. Such calibration is time consuming and tedious. Furthermore, the relationship between neutron count rate and soil water content does not seem to be unique, as variations occur with seasonal changes in organic matter, bulk density, the presence of neutron absorbers such as boron, cadmium, and chlorine, and the bound water content of the soil.

Some useful conversions

- Moisture content in Kg/m^{3}of soil = water depth in mm/m depth of soil (i.e., Kg/m^3= mm/m).
- Moisture content in percent volume (% vol.) = water depth in cm per meter depth of soil (cm/m); that is X% (by vol.) = Xcm/m, where X is the moisture reading
- Moisture in X% vol. = ($X \times 0.1$) Kg/m^3
- Moisture content in weight basis × soil bulk density = Moisture content in percent volume (% vol.)

Analyzing the Moisture Data

The soil moisture data that are taken with the radiological method can be analyzed in two methods:

Method 1: Total profile moisture,

$$\begin{aligned} M_{\mathrm{T}} &= 1.5d_1 + d_2 + d_3 + \cdots + d_{n-1} + 0.5d_n \\ &= (1.5 \text{ times of water depth at first soil depth} \\ &+ 0.5 \text{ times of water depth at last soil depth}) \\ &+ (\text{sum of the water depths at intermediate soil depths}), \end{aligned} \tag{4.34}$$

where M_{T} is the total moisture (water) in depth (cm) upto a certain depth of soil, $d_1, d_2, \ldots, d_n$ are the amount of water expressed in depth (cm) at the 1, 2,. . . , n depth of soil.

For each reading, the water depth d_{i} is obtained as:

$$d_i = (V_i/100) \times L,$$

where V_{i} stands for volumetric moisture content at depth i and L stands for length of soil column considered (normally equal to the distance between two readings) for this moisture reading.

Method 2: Total profile moisture,

$$\begin{aligned} M_{\mathrm{T}} &= d_1 + d_2 + d_3 + \cdots + d_{n-1} + d_n \\ &= \text{sum of all water depths upto the desired level}, \end{aligned} \tag{4.35}$$

where M_{T} is the total moisture (water) in depth (cm) upto a certain depth of soil, and $d_1, d_2, \ldots d_n$ are the amount of water in depth (cm) at the 1st, 2nd,. . ., nth depth of soil.

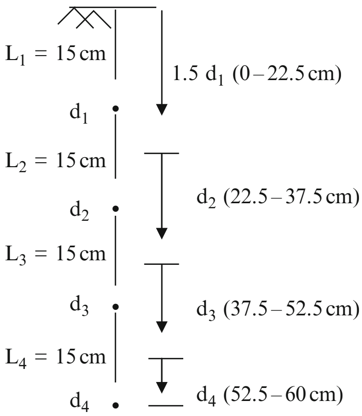
Philosophy of the First Method

Normally, the upper soil layer of the crop field becomes drier fast than the lower layers, and roots of most field crops are concentrated on this layer. Moisture content on this layer influences the plant growth and irrigation decision making process. If the radius of influence/measurement at 15 cm soil depth is 23 cm (e.g., corresponding to 25% moisture), it means that it is the average moisture percentage upto 46-cm depth. To account for the low moisture level at upper layer, this method is advantageous over the alternative method.

Examples Explaining Moisture Calculation

Example 4.4. In a wheat field, moisture readings are found as 25, 29, 31, and 35% by volume at a depth of 15, 30, 45, and 60 cm depth, respectively. Compute the total moisture upto (a) 60 cm soil depth, (b) 70 cm depth, and (c) 50 cm soil depth

Solution.



Moisture (in depth of water) for a particular soil depth, $d_i = (V_i/100) \times L$ Here, interval of moisture reading, $L = 15$ cm
Thus, the water depth corresponding to soil depths of 15, 30, 45 and 60 cm are 3.75, 4.35, 4.65, 5.25 cm.

Soil depth (cm)	15	30	45	60
Moisture reading (% vol.)	25	29	31	35
Moisture depth (in cm) for surrounding 15 cm soil depth	3.75	4.35	4.65	5.25

(a) Using the equation, $M_T = 1.5\, d_1 + (d_2 + d_3 + \cdots + d_{n-1}) + 0.5\, d_n$ and from the figure, total moisture upto 60 cm soil depth = $(1.5 \times 3.75) + (4.35 + 4.65) + (0.5 \times 5.25) = 17.25$ cm

(b) Here, depth interval can not taken as uniform up to 70 cm. Taking 15 cm from the bottom, the remaining depth = $70 - 15 = 55$ cm

Following the principle of the equation, $M_T = 1.5\, d_1 + (d_2 + d_3 + \cdots + d_{n-1}) + 0.5\, d_n$ and the above figure. Moisture upto 70 cm depth = $(M_{0\text{–}22.5}) + (M_{22.5-37.5} + M_{37.5-52.5} + M_{52.5-55}) + M_{55-70}$
$= 1.5\, d_1 + (d_2 + d_3 + d_4 \times 2.5/15) + d_n$

$= (1.5 \times 3.75) + [4.35 + 4.65 + (2.5/15) \times 5.25] + (5.25)$
$= 20.75$ cm

(c) Similar to (b), moisture upto 50 cm depth $= (M_{0-22.5}) + (M_{22.5-35}) + M_{35-50}$

$= 1.5\, d_1 + [d_2 \times (12.5/15)] + d_n$
$= (1.5 \times 3.75) + [4.35 \times (12.5/15)] + (4.65)$
$= 13.9$ cm

Example 4.5. Compute the soil moisture upto the depth of 60, 70, and 50 cm for the problem of Example 4.4 using the alternate calculation procedure.

Solution. Total profile moisture, $M_{\mathrm{T}} = d_1 + d_2 + d_3 + \cdots + d_{n-1} + d_n$
$M_{0\text{–}60} = 3.75 + 4.35 + 4.65 + 5.25 = 18$ cm
$M_{0\text{–}70} = (3.75 + 4.35 + 4.65 + 5.25) + (5.25/15) \times 10 = 18 + 3.5 = 21.5$
$M_{0\text{–}50} = (3.75 + 4.35 + 4.65) + (5.25/15) \times 5 = 14.5$ cm

Precautions and Protective Measures in Radiological Method

(a) Take protective measures in using and transporting the instrument.
(b) During operation of the instrument, the hand, mouth (eye), and feet are prone to have higher exposure of radiation. Gumboot (for feet) and hand-glove (for hand) can reduce the hazard to a great extent as these materials (polyethylene) contain sufficient hydrogen.
(c) Incorporating a polythene or water absorber at the soil surface can reduce the radiation hazard during probe reading at shallow soil surface.
(d) The neutron moisture gauges generate high voltages (~1 KV), which can cause severe shock. Before connecting or disconnecting the probe cable, or insertion or removal of any module, the unit must be turn off.
(e) Store the instrument 15 ft far away from normal movement of people to escape radiation hazard.

Advantages

(a) Once the instrument is calibrated, taking the moisture reading is straight forward
(b) Provide direct readout of volumetric moisture percentage
(c) No destructive sampling is required, once the access tube is installed, frequent moisture reading is possible at several depths
(d) Portable for multiple measurement
(e) Large number of moisture reading can be taken within short time

Disadvantages

(a) Poses radiation hazard.
(b) Requires site-specific calibration.
(c) Calibration of the instrument requires skilled personnel.

(d) Requires charging of the battery.
(e) Maintenance, servicing, and trouble shooting are difficult.
(f) Storing and transportation requires special care.
(g) The instrument is costly.
(h) Requires special permission/license to use such instruments because it contains radioactive material, therefore generally limited to only research stations.
(i) Interpretation of results can sometimes present difficulties, because the volume of soil in which neutron thermalization is gauged by the detector is never known precisely, and may have some degree of overlapping between two adjacent measurement points.
(j) There is difficulty in measuring moisture near the surface because a portion of fast neutrons escape into the atmosphere.
(k) Sources of hydrogen other than soil moisture can have an impact on the accuracy of reading. In the upper layer of organic soils where huge hydrogen present in the organic matter and the total porosity is so great that only the hydrogen in soil water is of any significance.

Limiting exposure of radiation from the instrument

Exposure can be kept to a minimum with the following three principles:

- By reducing the time of exposure (contact/operation time)
- By maintaining distance from the source
- By adopting protective measures

The simple way to reduce radiation exposure is to reduce the time spent around the source. If the time is reduced to half, the exposure is reduced to half, subject to all other factors remain constant.

Maintaining distance from the radiation source is another effective way to reduce exposure. Exposure rate is inversely related to the square of the distance from the source, i.e.

$$\text{Exposure} \propto \frac{1}{(\text{Distance})^2}$$

If the distance from a radiation source is doubled, the exposure rate is reduced to one-fourth its original value. Similarly, if the distance is tripled, the exposure rate is reduced to one-ninth.

Another means of minimizing exposure is adoption of protective measures. There is a common wise saying, “prevention is better than cure.” Protective measures such as warring apron, protecting radiation-prone zone of the body (for foot, hand, and mouth) with gumboot, glove, and glass can reduce the exposure to a minimum.

Gamma Attenuation Method

Another radioactive technique for measuring soil moisture is the gamma ray absorption method. In this method, a probe containing a source of gamma-rays and a Geiger detector are accurately located in the soil profile at the same depth but an arbitrary distance apart. The absorption of gamma-rays is an indication of the soil moisture.

The main advantage of this method is that its zone of measurement is very narrow, and very accurate logging of moisture variation down a profile can be obtained. However, operating problems are such that this instrument does not have wide use.

4.4.3.4 Electromagnetic Method

Concept

Electromagnetic methods are based on measurements of electrical properties of soil, which are closely related to soil-water. There are several types of electromagnetic method, each with advantage and disadvantage.

One approach of soil-water estimation measures the dielectric constant of the soil water medium and then estimates soil-water content. This category includes time domain reflectometry (TDR), frequency domain reflectometry, soil capacitance measurement, TDR FM, etc. TDR is accurate and automatable method for the determination of water content and electrical conductivity of porous media.

Another approach is resistivity method. Gypsum blocks are within this category.

The TDR Instrument

A reflectometer is an instrument that measures reflections. A time-domain instrument performs its function by measuring the time. The time-domain reflectometer measures the reflections of a launched voltage pulse in time. The reflections and their corresponding times are used to obtain the measurements intended for.

Principle

Water content of soil is inferred from the dielectric permittivity of the medium. Electrical conductivity is inferred from TDR signal attenuation.

Theoretical

The TDR instrument is based on some of the basic principles of electric circuits for alternating and direct currents. The major circuit characteristics that TDR utilizes are the capacitance, inductance, resistance, conductance, reactance, and impedance.

Nonconductive materials or insulators are usually known as dielectrics. These dielectrics are polarized in the presence of an electric field by induction and store electrical energy. The capacitance of a capacitor depends upon the characteristics of the dielectrics between the two parallel plates. A measure of these characteristics of the dielectrics is called the *dielectric permittivity*. It is the capacitance between two parallel-plate conductors of 1 m^2, separated by 1 m. The dielectric permittivity of a material relative to the value of the permittivity of free space is termed as relative dielectric constant or simply the *dielectric constant*.

The TDR actually measures the velocity of propagation of an electromagnetic wave in a medium at a microwave frequency. The response to the electromagnetic excitation in most soil is a function of the free water content and is much greater than that in dry soil. The soil–water–air system acts as a dielectric material. The bulk dielectric constant of a soil is governed by the water content of the soil because of its very high dielectric constant.

The velocity of the TDR pulse in the soil is calculated from the length of the sensor and the time travel of the pulse through the sensor. The expression for the velocity in mechanics is:

$$v = \frac{2L_{\mathrm{s}}}{t}, \tag{4.36}$$

where v is the velocity of propagation of the TDR pulse in the soil (ms^{-1}), L_{s} is the length of the sensor in the soil (m), T is the transit time of the pulse for a return trip in the soil through the length of the sensor (L_{s}, s). But in electrodynamics, the velocity is expressed as:

$$v = \frac{v_0}{\sqrt{\varepsilon}}, \tag{4.37}$$

where v_0 is the velocity of the pulse in free space (ms^{-1}), ε is the dielectric constant of soil.

The dielectric constant of a soil is calculated by equating the velocities of the pulse derived from machines and electrodynamics. Thus, from the above two equations and using $v_0\, t/2 = l_{\mathrm{a}}/p$, the dielectric constant of the soil, ε, is expressed as:

$$\varepsilon = \left(\frac{l_{\mathrm{a}}}{L_{\mathrm{s}} v_{\mathrm{p}}}\right)^2, \tag{4.38}$$

where l_{a} is the apparent distance traveled by the TDR pulse for a complete return trip through the sensor (m), L_{s} is the length of the sensor (m), v_{p} is the ratio of the velocity of an electro-magnetic wave in a medium to that in the free space.

Soil-water content can be correlated to the dielectric constant by taking into account the effects of organic matter content and bulk density of the soil. Calibration function can be developed using the refractive index of the soil, which results in a linear relation between the dielectric constant and soil-water content. The linear calibration of Ledieu et al. (1986) is used widely to determine the water content of soil (θ) accurately (±0.01%, by volume) from the measured dielectric constant, ε. Their equation is:

$$\theta = 0.1138\sqrt{\varepsilon} - 0.1758.$$

TDR Options

A variety of TDR systems are available for water content determination in soil and other porous media. Different TDR probe configurations provide users with site- and media-specific options. A TRD consists of several components: a pulser (generating short time pulse), voltage detector (receiver), timing system, sensor, and display unit.

TDR Sensors

TDR is a very versatile technique. Different configurations of the transmission lines can be chosen to meet the specific requirements of the selected problem. Several configurations of TDR sensors are available: balanced parallel two-wire sensors with an impedance-matching balun, unbalanced parallel two-wire sensors without a balun, unbalanced coaxial cylinders, unbalanced parallel multi-wire sensors (Baker and Lascano 1989; Heimovaara and Bouten 1990; Malicki and Skierucha 1989) (Fig. 4.9). In practice, parallel two-wire and three-wire sensors are most commonly used. The optimum efficiency in the measurement is obtained by matching the characteristic impedance of the coaxial cable connected to the sensor. Three-wire sensors give neater reflection and permit more reliable and accurate analysis of the signal compared with two-wire sensor. The TDR sensor can be constructed with any nonmagnetic material having an electrical conductivity much greater than that of the medium of measurement.

Method

A TDR sensor/probe is inserted into the soil and a step-voltage pulse is launched from a TDR instrument through a coaxial cable to the sensor. The sensor serves as a wave guide and the soil as the dielectric medium. A part of the voltage pulse is reflected back when it enters the sensor from the coaxial cable. Another part reaches the end of the sensor and is then reflected back to the source. These reflections occur

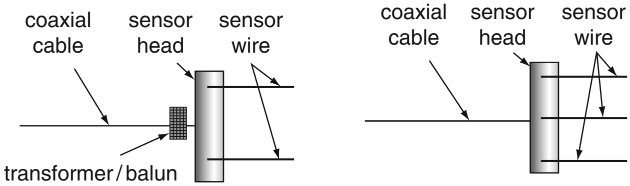


Fig. 4.9 TDR configurations (**a**) balanced parallel two-wire sensors (*left*), (**b**) unbalanced three-wire sensor (*right*)

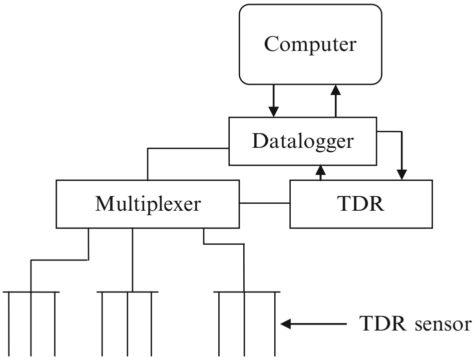


Fig. 4.10 Schematic of TDR settings

due to the change of impedance in the transmission line. The TDR measures the average volumetric water content of the volume of soil influenced by the sensor (Fig. 4.10).

Advantages of TDR over other techniques

1. No radiation hazard as associated with neutron probe or gamma-attenuation technique
2. Provide direct readout of volumetric moisture percentage
3. Capable of providing continuous measurement through automation and multiplexing
4. Nondestructive technique
5. Superior accuracy over other soil-water content measurement methods, accuracy to within 1 or 2% volumetric water content
6. Calibration requirements are minimal
7. Has spatial and temporal resolution

Disadvantages

1. The instrument is costly, thus not accessible to all.
2. Requires technical hand to operate.
3. It has complex electronics, and thus troubleshooting is difficult.

4.4.3.5 The Diviner

Description

Exploiting the principle of dielectric property of the soil, a device called DIVINER has been developed to measure the soil moisture quickly (Sentek 2007). It is a very fast and accurate method for determining soil moisture. Moisture content (% volume) is measured by responses to changes in the dielectric constant of the soil.

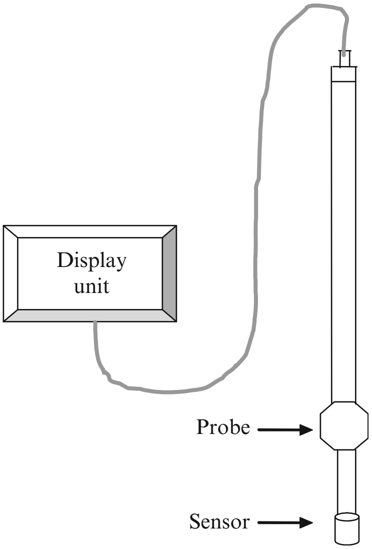


Fig. 4.11 Schematic representation of a diviner

The instrument is simple. Specialized access tubes are installed in the field with the supplied cutting tool. After installing the tube, it is sealed with specialized cap controlled from the ground (Fig. 4.11). During operation, the control unit is set to the respective calibration equation and other operational modes. The probe is then pushed downward through the access tube and pulls out of the tube again. The moisture readings at 10-cm interval are shown in display and recorded in memory. Time needed for moisture reading in one tube is about 10∼20 s. A large number of readings can be taken within very short time.

Advantages Over Other Tools/Techniques

- No radiation hazard
- Quick responsive time
- Lack of random counting error
- Handy and lighter equipment
- Easy to operate
- Relatively cheaper than the Neutron Moisture and TDR

4.4.3.6 Electrical Resistance Block/Gypsum Block

Electrical resistance meters can be used to measure moisture content of the soil. The electrical resistance between two wire grids embedded in a block of gypsum or similar material (i.e., permanently embedded in the soil) is measured. As the soil dries, the block loses water and the electrical resistance increases. The change in resistance can be interpreted in terms of soil water content. The blocks should be calibrated for each soil type and each depth, if the profile soil texture varies from each other.

Principle of the Method

The method measures the change in electrical resistance between two electrodes embedded in a porous material, which is in moisture equilibrium with the surrounding soil. The electrical resistance of the porous block is proportional to its water content. The electrical resistance varies with the moisture content of the soil, which in turn indicates the soil moisture content.

Requirement

Because of electrolysis, an A.C. measuring instrument is required.

Description

The blocks are placed in the soil at the location where the water content measurement is desired. It should be located in the root zone. The number and depth depend on the crop and depth of effective root zone. Generally, three observation points are recommended – the lowest point of the root zone, midway from the soil surface (at the maximum root zone position), and a near surface (uppermost root zone position). The porous blocks absorb water from the surrounding soil, and electrical resistance in the block corresponds to water content. The lower the resistance, the greater the water content.

Advantages

- Relatively cheap
- Once calibrated requires minimum calculation
- Allow continuous soil water measurement
- Can be implemented easily in the soil

Disadvantages

- Time lapse before reliable measurements are restored
- Do not work well in coarse textured (high porosity), saline, swelling, and dry soil.
- The blocks need to soak in water before setting in the field
- Blocks need to replace every 2$\sim$3 years

4.4.3.7 Tensiometry Method

This method measures the potential or energy of soil water. One such instrument is tensiometers (Fig. 4.12). Soil-water is brought into equilibrium with water in a porous sensing element, usually ceramic, which is connected to a manometer or suction gauge, and the actual free energy or potential is read directly in appropriate energy units. Tensiometer readings indicate the relative wetness of the soil (high

Fig. 4.12 Tensiometers of different sizes (*Courtesy*: Soil Moisture Co.)

readings indicate a dry soil, low readings indicate a wet soil). With appropriate calibration, the reading can be converted to percentage soil water.

Principle of the Method

When the water-filled (atmospheric pressure) porous ceramic cup of the tensiometer comes into contact with the dry soil (negative pressure), the water from the cup comes out until equilibrium is reached. The resulting rise in mercury in the tube (in case of mercury tensiometer) or the deflection of the gauge (in case of gauge tensiometer) indicates the soil-water tension.

Drawbacks/Limitations of Tensiometer

(a) The main drawback of this technique is that it covers only a limited range of soil moisture scale, ranging from pF 1 to pF 2.7 (0–0.8 bar). Beyond this limit, air enters the system, which then ceases to be accurate and soon breaks down completely, requiring recharging with air-free water. Thus, the tensiometers are less suited to use in fine-textured soil in which a small portion of the plant available moisture is held at a tension less than 0.8 bar.

(b) If the pores in the tensiometer are very small, the range can be extended slightly, but the response time for fluctuations in soil potential becomes excessive. If the sensor is large with relatively coarse pores, it can temporarily alter the soil environment by excess flow of water from the device into the soil.

(c) Tensiometer readings reflect only the soil moisture tension (which is surrounding the porous cup), but not the amount of water held in the soil. To know the soil moisture content, it needs to have soil moisture characteristic curve relating tensiometer reading.

Field of Use

The main use of tensiometer is in programming irrigation of crops with high water demand (water sensitive crop) or in propagating work in nurseries.

Working Method

As the tensiometers measure the soil-water tension, a calibration curve is needed to know the moisture content. Calibration curve is made under controlled condition with careful monitoring.

Preparing a Calibration Curve

To prepare a calibration curve, tensiometer reading and gravimetric determination of soil moisture are done simultaneously. For this purpose, a plot of about 4 m × 4 m is taken and a dike of about 30 cm height is constructed. After leveling the plot, several series (3–4) of tensiometers at different depths are installed. Water is applied in the plot till 4–5 cm water stands in the plot. Two to three days after disappearance of standing water, tensiometer readings are taken and soil samples are collected depth-wise for gravimetric moisture determination. Procedure for gravimetric moisture determination and necessary precautions are described in an earlier section. Volumetric moisture content is obtained by multiplying the weight basis moisture by its bulk density. Soil sampling with core provide the volume of soil directly and hence facilitate volumetric water content directly.

After determining moisture content, plot the soil moisture content (weight or volume basis) against the tensiometer reading on simple graph paper. This curve is termed as calibration curve, and can be used to know the soil moisture content for any tensiometer reading.

Taking a Reading for Moisture Determination

Before setting in the field, the tensiometer is checked in the laboratory for accuracy (whether the porous cup transmits water properly, and the gauge deflects properly). The ceramic cup is inserted alternately in dry-sand and in a water-pot. If the gauge shows some reading/deflection in sand and zero reading in water-pot, then it is OK.

In the crop field, the tensiometer is installed with several replications. The number of depth depends on soil type and effective root zone depth (within which about 80% roots are concentrated). Plants having effective root zone <45 cm, only one depth is sufficient. After reaching equilibrium with the soil water (normally after 24 h), the reading is taken. Using the calibration curve, the moisture content is determined. The drier the soil, the higher the suction and more water will be sucked from the ceramic cup, resulting higher gauge deflection or rise of mercury in the tube (Fig. 4.13). For most purposes, taking a reading early in the morning is sufficient. Frequency of reading should be such that change in reading is not greater than 10–15 centibars. The time to irrigate the crop is determined by the reading of tensiometer, which is near the bottom of active root zone (where most living roots exists).

In case of open end (U-tube) water tensiometer, the drop in water level "*h*" indicates that it has been sucked into the soil, thus an index of magnitude of the potential. The magnitude of pressure is:

$$\mathrm{P} = \omega h, \tag{4.39}$$

where ω is the density of liquid and h is the height of the liquid.

The manometers can be filled with immiscible liquids, such as mercury, water. Use of mercury has an advantage that a short height indicates a large pressure difference due to its high density (13.6 gm/cm^3).

If the tensiometer is out of water or leaking, the reading will remain at zero. Several consecutive zero readings are a sign of tensiometer malfunctioning. Then it should be checked thoroughly.

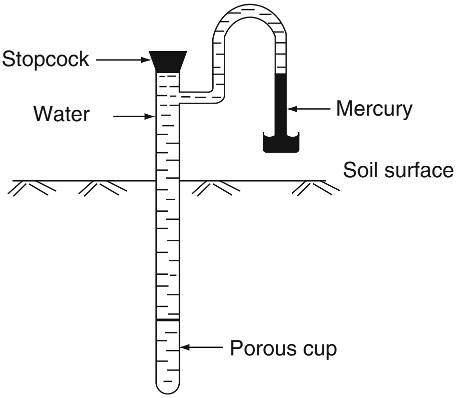


Fig. 4.13 Sketch of mercury tube tensiometer

Table 4.6 Approximate tension at which irrigation should be applied for optimum yield

Crop	Matric potential (cm of water)
Cabbage	−350 to −600
Cauliflower	−600 to −700
Lettuce	−450 to −650
Potato	−400 to −600
Tomato	−900 to −1,400

In essence, the tensiometer readings indicate relative wetness of the soil. A reading of zero (0) indicates a saturated soil. A reading of higher than 50 centibars indicates that irrigation may be needed for some crops (depending on crop type). An approximation of tension for some crops is given below (Table 4.6):

4.4.3.8 Quick Draw Moisture Meter Method

This instrument works with the same principle of tensiometers (Fig. 4.14). Moisture reading can be obtained within shorter period.

Fig. 4.14 Quick draw moisture meter (*Courtesy*: Soil Moisture Co.)

4.4.3.9 Hand-Feel Method

This is a crude but faster and simple method for estimating soil moisture. It requires experience. One of the drawbacks of this method is that the estimation of soil moisture is subjective and is not an exact amount of moisture. However, if a person has experience in the hand-feel method (how different soils feel and appear at different moisture contents) and is comfortable in this method, this is an acceptable method. The hand-feel method will allow for more locations to be sampled. Gravimetric soil sampling can back-up results from the hand-feel.

4.4.3.10 Other Advance Methods

Psychrometer Method

This approach measures the vapor pressure of the water in equilibrium with the soil and hence measures the total soil-water potential. The technique has been used mainly in the laboratory under rigorous controlled conditions, but is now showing up in the field. In its simplest form, the extension of a strip of Cellophane in a gauge container embedded in the soil is read remotely by the change of resistance in a frictionless potentiometer linked to the system. However, the more precise thermocouple psychrometers are now being used widely. This technique is one of the main tools of the plant physiologist in measuring water stress in plants.

Thermal Methods

The possibility of correlating thermal properties of soils with moisture content was explored by Shaw and Baver (1939), who devised a heat-dissipation cell for this purpose. Others have modified the technique. Although in practice it works satisfactorily, it requires calibration for each sampling site.

Nuclear Magnetic Resonance Method

In this technique, resonance induced by a radio-frequency electric field is used on certain atomic nuclei in a strong magnetic field. Careful selection of radio frequency in relation to magnetic field strength can make this device specific for hydrogen, which means that small soil samples can be processed rapidly for determination of hydrogen and thus for soil moisture. The commercial instrument “N.M.R. spectrograph” could be used for such measurements.

4.4.4 Soil-Water Potentials and Other Related Terminologies

Water in soil is subject to several forces originating from the presence of the soil solid phase, dissolved salts, gravitational field, and from the action of external gas pressure. These effects may be quantitatively expressed by assigning potentials to the soil water. The sum of these potentials is designated as "total potential of soil water" or simply "soil water potential."

4.4.4.1 Total Potential of Soil Water

Soil-water potential *or* total soil-water potential (or in short, total potential) is the amount of work that must be done per unit quantity of pure water to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the soil water at the point under consideration (ISSS 1963). Here, the soil-water is understood to be the equilibrium solution in the soil; pure water refers to the chemically pure compound H_2O.

In essence, soil-water potential represents the energy required to remove water from the soil. Total potential consists of the following components:

- Osmotic potential
- Capillary or matric potential
- Gravitational potential
- Potential due to external gas pressure

Mathematically, it can be expressed as:

$$\psi_t = \psi_{os} + \psi_m + \psi_z + \psi_p. \tag{4.40}$$

Osmotic Potential

It is due to the presence of salt in soil water (i.e., due to energy effects of solutes in water). Osmotic potential is the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure, to a pool containing a solution identical in composition with the soil water (at the point under consideration) but in all other respects identical to the reference pool.

Capillary or Matric Potential

It is due to the capillary forces of the soil pores (i.e., inherent to soil matrix). Capillary potential or matric potential is the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool containing a solution identical in composition to the soil water at the elevation and the external gas pressure of the point under consideration to the soil water.

Gravitational Potential

It is based on elevation above the reference point. It can be defined as the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure, to a pool containing a solution identical in composition with the soil water (at the point under consideration) but in all other respects identical to the reference pool.

The sum of gravitational potential and matric or capillary potential is termed as hydraulic potential (ψ_h).

The basic unit of water potential is energy per unit mass, Jkg^{-1}. Other units are pascal (Pa), bar, atmosphere (atm), meters (m) of water, pF. The pF is the inverse of logarithm to the base 10 of the absolute head of water expressed in centimeter of water. That is,

$$\mathrm{pF} = \frac{1}{\log_{10} h}. \tag{4.41}$$

The relations among different units are:

$$\mathrm{Jkg}^{-1} = \gamma \times \mathrm{Pa} = \mathrm{m/g},$$

where γ is the density of water (1,000 kg m^{-3}), and g is the gravitational acceleration (9.81 m s^{-2}).

4.4.4.2 Related Terminologies

Hydraulic Head

This is the elevation with respect to a specified reference level at which water stands in a piezometer connected to the point in question in the soil. The hydraulic head in system under atmospheric pressure may be identified with a potential expressed in terms of the height of a water column. It is the sum of gravitational and matric (or capillary) potentials.

Differential Water Capacity

It is the absolute value of the rate of change of the water content with matric or soil water suction. The water capacity at a given water content will depend on the particular desorption or adsorption curve employed.

4.4.5 Determination of Soil Moisture Characteristics

4.4.5.1 Conceptualization of Soil Moisture Characteristics

The amount of soil-water is usually measured in terms of water content as percentage by volume or mass, or as soil-water potential. Water content neither necessarily describes the availability of the water to the plants nor indicates how the water moves within the soil profile. The only information provided by water content is the relative amount of water in the soil. Soil-water potential does not directly give the amount of water present in the root zone. Therefore, soil-water content and soil-water potential should both be considered when dealing with plant growth and irrigation.

Definition of Soil Moisture Characteristics

The graphical representation of the relationship between soil water suction (ψ) and soil water content (θ) [$\theta(\psi)$] is called a soil moisture characteristic curve (SMC) or moisture release curve or soil-water retention curve. A typical soil moisture characteristic curve is shown in Fig. 4.15. The nature of the soil moisture characteristic curve depends on the physical properties of the soil such as texture, structure, and organic matter content.

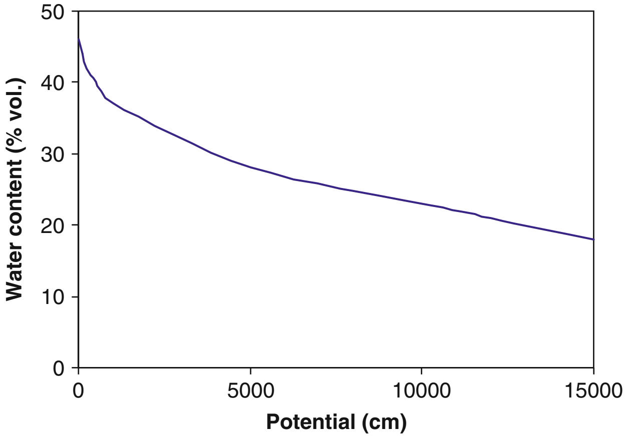


Fig. 4.15 Typical soil moisture characteristic curve of a loamy soil

Importance of Soil Moisture Characteristics

SMC is one of the two basic hydraulic properties of a soil. Along with the hydraulic conductivity function, it controls the hydrology of field soils. Using capillarity theory, the SMC can also be used to infer an approximate soil pore size distribution. This relationship has also been used to estimate the other basic relationship, between unsaturated hydraulic conductivity and soil-water content.

Methods for Determining SMC Curve

As mentioned earlier, the soil moisture characteristics is the relationship between soil-water content (θ) and matric potential (ψ). This relationship can be obtained in two ways:

1. In desorption, by taking an initially saturated sample and applying increasing suction
2. In sorption, by gradually wetting up an initially dry soil sample while reducing the suction

Each of these two methods yields a continuous curve, but the two curves will in general not be identical. The equilibrium soil wetness at a given suction is greater in desorption (drying) than in sorption (wetting). When a partially wetted soil commences to drain, or when a partially desorbed soil is re-wetted, the relation of suction to moisture content follows some intermediate curve (Hillel 1980). The ψ–θ relationship can thus become very complicated. Because of its complexity, the hysteresis phenomenon is often ignored, and the desorption curve, also known as soil-moisture release curve, is used.

Details of the phenomenon hysteresis will be described in a later section.

4.4.5.2 Moisture Determination at Low Tension

Within the low tension range, a significant amount of water is released from the soil, especially in clay soil, than that within high tension range. So it is important to apply tension and quantify the soil moisture at low tension. But with the pressure plate apparatus, which is used to determined moisture at high tension range, it is difficult to fix up the tension. In addition, the pressure plate apparatus is not well suited for low tension because of their inherent structure. For these difficulties, the researchers have been devised a range of techniques to determine soil moisture at low tension. Commonly used techniques are as follows:

(a) Porous plate method
(b) Sand table method
(c) Hanging column technique

All these techniques are based on the same basic principle. Soil (soil core) is placed on porous medium, and suction is created and maintained through different techniques. The suction is transmitted through the medium to the core soil-water, and the sample is allowed to attain equilibrium with the suction. The soil-water content is then determined.

Collection and Preparation of Core-Soil Sample

Core samplers of (5 cm × 5 cm) are normally used to obtain vertical soil samples at different soil depths. First, representative site of the field is selected. The upper surface (0–5 cm) is removed. Then the core sampling is started. The cores are inserted into soil with hammer or mechanical device. The cores are separated with care so that cores are filled with soil. Each sample is them marked, wrapped with polythene, clipped with rubber band, and stored in cooled place.

Both for low tension (porous plate and others) and high tension (pressure plate determination), it is advisable to cover the core sample by a thin nylon cloth (to avoid soil mining) and establish good contact with with kaolin clay before placement in porous plate.

Porous Plate Method

A variety of porous materials may be used such as ceramic plate, sintered glass, asbestos, kaolin clay, blotting paper, sand passing 1.5-mm sieve, etc.

In this method, the wetted porous material is placed on a funnel or a funnel type plate, and the saturated soil sample is placed over it (Fig. 4.16). The porous material and the soil are wetted to facilitate a continuous flow system. The area outside the soil sample is covered with a thick layer of clay. The funnel is connected to an adjustable manometer. First, the manometer tube is filled with water. Then the water level is lowered to the desired level. Lowering of water from the manometer limb places a suction head on the soil, and soil-water is consequently withdrawn until the soil-water suction balances the applied suction. After equilibrium, the sample is removed and weighed for determining water content.

The applied suction can be varied and the resulting equilibrium soil moisture content can be determined.

Sand Table Method

A sand table is simply a carefully prepared, completed saturated column of fine sand to which suction can be applied without air entry. Soil samples are placed on top of the sand and the applied suction is transmitted to them.

Any air-tight container having a drainage outlet can be used as a sand box. Two types of arrangement can be made (Ali 2000; Ali and Turral 2001): (a) drainage pipe at the side (Fig. 4.17) and (b) drainage pipe at the bottom.

With this technique, moisture at 100–200 cm tension can be determined provided the sand table is set up at a elevated table (higher than the tension required), and the outlet is fixed at corresponding height difference.

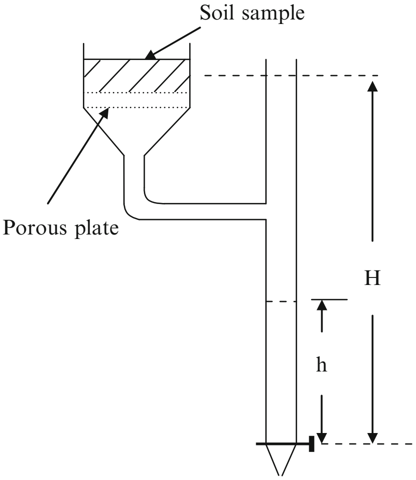


Fig. 4.16 Schematic of arrangement of porous plate method

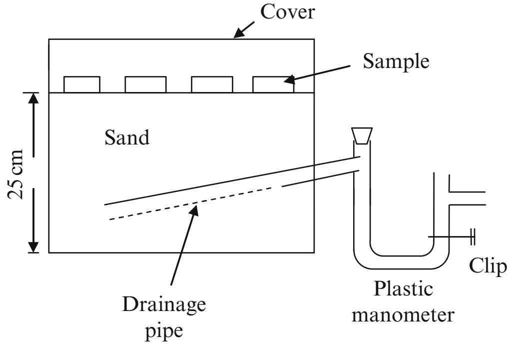


Fig. 4.17 Schematic of sand table arrangement (after Ali and Turral 2001)

Drainage Pipe at the Side

The container is drilled at the side to insert the slotted drainage pipe with "T" arrangement. Upward slope of the drainage pipe assists the removal of air. The slotted drainage pipe is wrapped with nylon cloth 2–3 times to prevent siltation. It is ensured that the drainage pipe is well sealed into container. Appropriate graded sand is collected and washed out, and filled in the container nearly 2/3rd portion. Water is added to the container and the manometer is opened to remove the air. Then the outlet of the manometer is kept at the same level of the sand in the box.

The saturated soil samples (covering with nylon cloth and attaching with kaolin) are then placed on the sand box with a slide twist to facilitate proper hydraulic contact. The sand surface (other than the core samples) is then covered with clay having 2–3 cm thick layer, and the box is covered with shield or plastic cover. Then the outlet of the manometer is lowered to the desired level (specific suction head) and allowed for equilibrium. After the equilibrium has been reached, the samples are taken out, weighed, and placed for next suction or setting, or placed in oven for dry.

Drainage Pipe at the Bottom

In this case, the drainage pipe is attached at the bottom of the sand-table. Other working principles are similar to that of the drainage pipe at the side.

Both porous plate and sand-table methods are suited to determine moisture retention at a suction about 100–150 cm.

4.4.5.3 Moisture Determination at High Tension

By Pressure Plate Apparatus

Principle of Pressure Plate Desorption Method

Pressure plates are used to provide information on soil-water desorption for matric potential of 0.5 bar to -15 bar. Drying of the soil is achieved by applying a sequence of pressure inside the container. The pressure applied within the container decreases the matric potential of the water in the plate, resulting in movement of the water from the soil through the plate.

Description of Pressure Plate Apparatus

Placement of samples over pressure plate within the pressure chamber is shown in Fig. 4.18, and the laboratory set up of the whole assembly is shown in Fig. 4.19.

Materials and Methods

After using for low tension measurement (in sand table or hanging column), the same samples are used to determine moisture retention at high tension in pressure plate apparatus. It is to be mentioned here that using different samples for low and high tension separately may result in ambiguous results. The detail working procedure of pressure plate measurement is given below:

- The ceramic plate is saturated under submerged condition for about 36–48 h.
- A slurry of kaolin is prepared and spread 1–3 mm thick over the nylon cloth-covered end of the cores. The weight of cloth and band is recorded before placement of slurry. Immediately, each core is placed upright on the saturated ceramic plate, and hydraulic contact is achieved by a slight twist applied to the core.

Fig. 4.18 Sketch of placement of samples over pressure plate within the pressure chamber (*Courtesy*: Soil Moisture Co.)

- The pressure vessel is closed, and pressure is applied gradually to the desired first level, and allowed drainage to take place until equilibrium is achieved (equilibrium time for different pressures are cited in Table 4.7).
- A ceramic plate corresponding to the next pressure is subjected to saturation.
- The core samples are removed from the plate after the equilibrium time, all hydraulic contact media are removed, and the samples are weighed (including nylon cloth).

The volume difference between that of the soil at equilibrium pressure and the initial is monitored.

- The kaolin slurry is spread over the cloth, the sample is placed over the new pressure plate and hydraulic contact is reestablished.

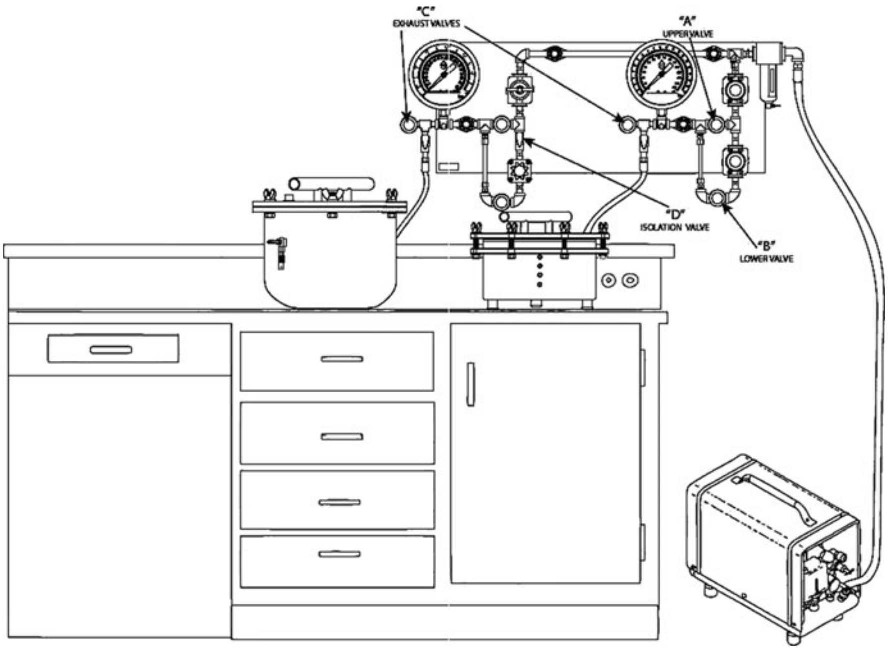


Fig. 4.19 Diagram of laboratory setting of pressure plate apparatus (*courtesy*: Soil Moisture Co.)

Table 4.7 Equilibrium times for 6-mm height core under different pressure

Potential (bar)	Equilibrium time (days)
0.3	3–5
1.0	7–8
5.0	10–12
10	15–17
15	20–22

- The next preselected pressure is applied, and the procedure is repeated upto the final *or* highest pressure (usually 15 bar).
- After the final equilibrium, hydraulic contact medium is removed, and the samples are weighed. At this stage, volume changes of the samples (for swelling clay) are recorded.
- The samples are placed in oven and dried at 105°C until constant weight is achieved.
- The samples are removed from the oven, allowed to cool at room temperature (preferably in a desiccator), and reweighed.
- The soils are then removed from the cores, which are then weighed.
- Height and diameter of the core are measured and recorded.

Then, the moisture content at different pressure is determined using the following formula and general mathematical principles.

Moisture content at a particular pressure, in % vol. = (wt. of soil sample after application of that pressure−wt. of over-dry soil)/vol. of the soil sample

Example on Moisture Calculation from Pressure Plate Calculation

Example 4.6. In a trial with pressure plate apparatus having 5-cm height core, a sample was run at different pressure settings and the following readings were recorded:

Wt. of empty core + nylon cloth and rubber band = 85 gm
Wt. of wet soil (including core) equilibrated with saturated sand = 610 gm
Wt. of oven-dry soil = 385 gm
The wt. of soil cores (soil + core + nylon cloth and rubber band) at different pressure settings are as follows:

Pressure (bar)	0.3	1	5	7	10	12	15
wt. (gm)	600	590	570	560	550	540	535

Determine the following:

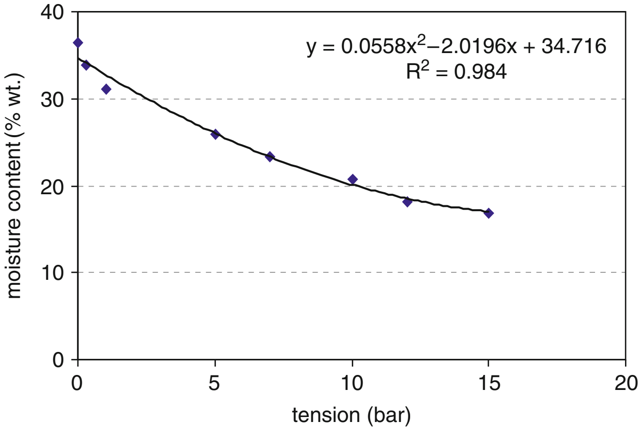
(a) Moisture at field capacity and wilting point
(b) Draw the moisture characteristic curve
(c) Develop equation relating tension vs. moisture content

Solution. Net wt. of oven-dry soil = 385 gm

The core (5 cm ht.) is equilibrated in saturated sand at average tension of (0 + 5)/2 = 2.5 cm = 0.00247 bar
The calculation results can be summarized as follows:

Tension (bar)	Gross wt. (core + wet soil + cloth, rubber) (1)	Core plus cloth and rubber wt. (2)	Net wt. of wet soil at that tension (3) = (1)−(2)	Net wt. of oven-dry soil (4)	Wt. of water in sample (5) = (3)−(4)	Moisture (% wt.) (6) = 100 × (5)/(4)
0.00247	610	85	525	385	140	36.4
0.3	600		515		130	33.8
1	590		505		120	31.2
5	570		485		100	26.0
7	560		475		90	23.4
10	550		465		80	20.8
12	540		455		70	18.2
15	535		450		65	16.9

Thus, the moisture at field capacity = 36.4% by wt. (water retained against gravity)
Moisture at wilting point = 16.9% by wt. (at 15 bar)
The relation between tension and moisture content is presented graphically in the figure given below:



4.4.5.4 Indirect Estimation of Soil Moisture Characteristic

The soil moisture characteristic (SMC) and hydraulic conductivity are the fundamental property controlling soil water storage and movement. The SMC data are needed for predictions of these processes. However, these data are difficult and expensive to measure. So procedures enabling their prediction from limited data are attractive.

In the laboratory, soil-water constants are determined using pressure plate equipment. This process is not only expensive but also time consuming. There is a wide acknowledged need for reliable and economical methods for determining these hydraulic properties. The need for parameterization of the soil water simulation models is a major motivation for the development of methods of predicting the SMC from limited data. There have been a number of attempts to predict the soil water characteristics from soil particle-size distribution (PSD) data. The availability of PSD data, and in some cases, the similarity between the shapes of the SWC and cumulative particle size distribution motivated such attempts. In general, two approaches have been taken to predict the SMC:

1. Statistical approaches, which either relate parameters in specific hydraulic models with texture and other soil properties using regression analysis (Woston and van Genutchen 1988), or else relate texture and other soil properties to water contents at specific matric potential, again using regression analysis (e.g., Gupta and Larson 1979).
2. Physico-empirical approaches, which transform the PSD curve into a soil water characteristic curve by relating soil particle size to a corresponding pore diameter in a soil capillary model (Arya and Paris 1981).

Statistical Approach

From Soil Physical Properties

Many attempts have been made to estimate the soil moisture properties from easily measurable soil parameters. Such parameters include textural separates (% sand, silt, clay), bulk density, porosity, organic matter content, etc. In this method, measured soil-water contents are regressed (multiple regression) with selected parameters. For each tension (or soil-water constants), the regression equation is developed. The regression equation is then used to estimate soil-water constants (FC, WP, etc.) or retention.

For water content for a given matric potential, the general form of the relationship is:

$$\theta_{\mathrm{p}} = a + bx_1 + cx_2 + dx_3 + ex_4 + \ldots, \tag{4.42}$$

where x_1, x_2, x_3 are the soil parameters, b, c, d are the regression coefficients, and a is the intercept.

Gupta and Larson (1979) used the following form:

$$\theta_{\mathrm{p}} = a \times \text{sand } (\%) + b \times \text{silt } (\%) + c \times \text{clay } (\%) + d \times \text{organic matter } (\%) + e \times \text{bulk density}\left(\mathrm{g/cm^3}\right).$$

4.4.5.5 Soil Moisture Characteristic Function

A number of functions have been proposed to describe the relation between volumetric soil water content (θ) and soil matric potential (ψ). Some of the widely used equations are described below:

1. *Campbell equation*

Campbell (1974) developed a function to describe the relation between volumetric soil-water content and soil matric potential:

$$\theta = \theta_{\mathrm{s}}\left(\frac{\psi}{\psi_e}\right)^{1/b} (\psi < \psi_{\mathrm{e}}) \tag{4.43}$$

$$\theta = \theta_{\mathrm{s}}(\psi \geq \psi_{\mathrm{e}}),$$

where ψ is the matric potential at moisture content θ, ψ_{e} is the air entry potential, θ_{s} is the volumetric water content at saturation, $b = a$(fitted) constant.

The above equation can be fitted to the moisture characteristic data by regressing volumetric water content (θ) on the matric potential. Taking log, the above equation can be written as:

$$\ln\theta = \ln\theta_s + (1/b)\ln\psi_e - (1/b)\ln\psi$$

or

$$\ln\theta = A + B\ln\psi, \tag{4.44}$$

where

$$A = \ln\theta_s + (1/b)\ln\psi_e \tag{4.45}$$

and

$$B = -\frac{1}{b}. \tag{4.46}$$

The values of the constants A and B can be determined from linear regression of $\ln\theta$ on $\ln\psi$. The θ_s can be assumed to equal total porosity multiplied by 0.93 (an empirically determined allowance for air entrapment at field saturation; William et al. 1992), and ψ_e and b can then be determined using equation (4.45) and (4.46). The water content at air entry (θ_e) may be taken as 0.9 θ_s.

The Campbell function is based on the concepts of fractal scaling of the soil void space, and it has the advantage of simplicity.

2. *Van Genuchten function*

Soil-water content as a function of pressure head is expressed by the model of van Genuchten (van Genuchten 1980) as:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + (\alpha h)^{\mathrm{n}}\right)^{\mathrm{m}}}, \tag{4.47}$$

where θ is the soil moisture content (volumetric) at pressure h(h is positive), θ_r is the residual volumetric water content, θ_s is the water content at saturation (volumetric), m, n, and α are empirical coefficients.

Mualem (1976) proposed m as: $m = 1 - 1/n$. An average value of α can be taken as 0.5.

The independent parameters of the above equation (θ_r, θ_s, α, and n) have to be estimated from observed soil-water retention data. Among them, the saturated water content (θ_s) can be determined experimentally easily. Also the residual water content (θ_r) can be measured experimentally, for example, by determining water content on very dry soil. The residual water content is defined here as the water content for which the gradient ($d\theta/dh$) becomes zero. From practical point of view, it is sufficient to define $\theta_r$as the water content at some large negative pressure head, such as at permanent wilting point (−15 bar).

3. *Brook and Corey model*

The power-law equation of Brooks and Corey (1964) is:

$$\theta = \theta_r + (\theta_s - \theta_r)(\psi_b - \psi)^{\lambda}(\psi < \psi_b), \tag{4.48}$$

$$\theta = \theta_s(\psi \geq \psi_b),$$

where θ is the volumetric water content, θ_s is the water content at saturation (% vol.), θ_r is the residual water content (% vol.), ψ_a is the matric potential (in cm), ψ_b is the bubbling pressure, and λ is the constant.

The two parameter model of Campbell (1974) differs from Brooks and Corey (1964) that it assumes θ_r is zero.

On a logarithmic plot, the above equations result in straight lines, which join the bubbling pressure or air entry potential.

4.4.5.6 Hysteresis in Soil-Water Retention

Concept

Water content of unsaturated soil varies with different hydrological processes, such as infiltration, evaporation, and evapotranspiration. The dynamic change of soil-water content generally does not follow the same path of water-content vs. negative pressure head during wetting and drying (Fig. 4.20). The water content in a soil at a particular negative pressure head at wetting differed from that of drying (or drainage), this phenomena is termed as hysteresis. The same phenomenon is true for soil hydraulic conductivity. Hysteresis can significantly influence water flow and solute transport in variably saturated porous media.

Hysteresis refers to the nonunique relationship between the pressure head, h, and the water content, θ, in the soil-water retention function $\theta(h)$. The relationship displays considerable variations in θ for the same h depending upon the history of soil wetting

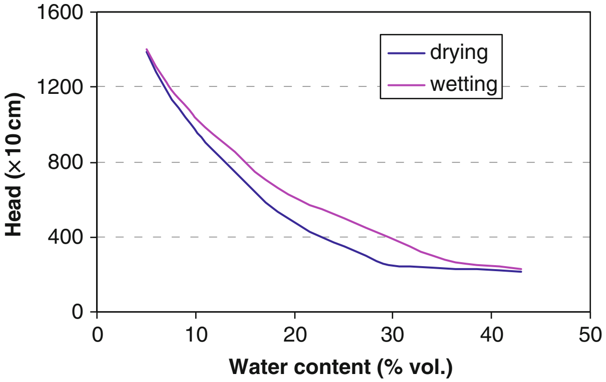


Fig. 4.20 Effect of hysteresis on the soil-water characteristic curve

and drying. During infiltration when the water content is monotonically increasing, the retention curve can be described by a unique function/curve. Similarly, during evaporation or gravity drainage when water content is monotonically decreasing, the retention curve can also be described by a unique but different function.

Factors Affecting Hysteresis

The factors influencing hysteresis are the following:

- Pore-size geometry
- Entrapped air
- Moisture absorption (capillarity) and release (drainage) behavior of the soil
- Swelling and shrinkage of soil

During wetting, the capillary pores are filled in first, then the medium and macropores. On the one hand, during drainage, the large pores become empty first, but the throats of micro-pores do not empty until the tension decreases enough against capillary effects corresponding to the pore diameter. As a result, some of the large pores that underlie the micro-pores will not empty until tension decreases below the threshold value. On the other hand, during wetting, the same large pores remain empty while the water enters the macro-pores. This type of differential behavior results in different shape of the soil-water characteristic curve.

4.4.5.7 Soil-Water Diffusivity

Definition, Importance/Significance, Measurement

Soil water diffusivity, $D(\theta)$, is the product of the hydraulic conductivity (K) and the slope of the soil water retention curve at a particular water content (θ), i.e.,

$$D(\theta) = K(\theta) \times \frac{\mathrm{d}\psi}{\mathrm{d}\theta}, \tag{4.49}$$

where ψ is the soil-water potential.

For analysis of plant water uptake, particularly in dry environment, knowledge of the soil-water diffusivity function at low water content is needed. Its unit is m^2/s. Diffusivity value changes much less than the hydraulic conductivity over the range of moisture content, thus easier to use in simulation model. Its typical value ranges from 1×10^{-9} to $3 \times 10^{-9} \mathrm{m}^2/\mathrm{s}$. Diffusivity can be measured/estimated by the following methods (Rose 1968; Passioura 1976):

- Evaporation under a turbulent condition
- By outflow data obtained by subjecting the soil sample to a single pneumatic pressure step
- Evaporation from intact soil and modeling the evaporation

Estimation of *D* from Intact Soil Core Evaporation

Working procedures are as follows:

- Undisturbed soil cores are collected from the field
- The samples are allowed to saturate from the bottom in a saturated sand box
- The samples are weighed after saturation (to determine initial soil moisture, θ_i)
- The samples are drained to a matric potential of 1 m (by a hanging column, placed in a sand box and wrapping the sand with kaolin or fine clay)
- Then the base of the samples are sealed and the top ($x = 0$) is subject to controlled, continuous flow of air for evaporation
- Weigh the sample and measure the evaporation from the top end ($x = 0$, where the initial moisture is assumed θ and final moisture content is θ_f)
- The evaporation process is continued until the evaporation rate becomes zero
- The following one-dimensional diffusion equation with customary boundary conditions is solved for diffusivity, *D*:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[D(\theta)\frac{\partial\theta}{\partial x}\right]$$

$$\begin{array}{lll} \theta = \theta_\mathrm{i}, & 0 \le x \le L, & t = 0 \\ \theta = \theta_\mathrm{f}, & x = 0, & t > 0 \\ \frac{\partial\theta}{\partial x} = 0, & x = L, & t > 0 \end{array} \tag{4.50}$$

- The above equation is solved numerically as:

$$\frac{\theta_{i,j} - \theta_{i,j+1}}{\partial t} = D_i\left(\frac{\theta_{i+1,j} - 2\theta_{i,j} + \theta_{i-1,j}}{(\partial x)^2}\right) + \left(\frac{D_{i+1,j} - D_{i-1,j}}{2\partial x}\right)\left(\frac{\theta_{i+1,j} - \theta_{i-1,j}}{2\partial x}\right)$$

- A constant boundary condition may be set at $x = 0$ by fixing $\theta = \theta_\mathrm{f}$, and zero flux boundary condition at $x = L$.

Indirect estimation

Miller and Bresler (1977) suggested a regression equation for estimating soil-water diffusivity function:

$$D(\theta) = 0.001\mathrm{m}^2\exp[8(\theta - \theta_\mathrm{d})/(\theta_\mathrm{w} - \theta_\mathrm{d})], \tag{4.51}$$

Where *m* is a constant relating visual position (distance, x_f) of wetting front at time $t = x_\mathrm{f}/(t)^{1/2}$; θ_d = water content of air-dry soil; and θ_w = water content of "satiated" soil at the wet of the column.

The quantities *m*, θ_d, and θ_w are obtained from the observations of infiltration of water of suitable quality into a horizontal column of air-dry soil.

Miller and Bresler (1977) used *satiation* to emphasize that the limit of spontaneous wetting is always less than saturation owing to air normally entered in spontaneously wetted pores.

4.4.6 Hydraulic Conductivity

4.4.6.1 Water Movement Through Soil

Water moves through soil as the following:

- Saturated flow
- Unsaturated flow
- Vapor flow

Saturated flow occurs when the soil pores are completely filled with water. Unsaturated flow occurs when the large pores are filled with air but small pores hold and transmit water. Vapor flow occurs when the vapor pressure differences develop in unsaturated and relatively dry soil. Vapor transmits from an area of high vapor pressure to an area of low vapor pressure. Hydraulic conductivity is the soil property that describes the ability of the soil with which the soil pores permit water (not vapor).

Concept of Hydraulic Conductivity

As mentioned earlier, hydraulic conductivity is the ability of a media to transmit fluid. It is the proportionality constant of Darcy's equation that defines the relationship between flux and hydraulic gradient.

$$Q \infty A \frac{h_1 - h_2}{L} \quad \text{or} \quad Q = KA \frac{dh}{L}, \tag{4.52}$$

where K is the proportionality constant or hydraulic conductivity.

It is the flux density (flow per unit area) when the hydraulic gradient is unity. Although its dimension is length per time (e.g., m/s), it is not a rate. As the gradient is a ratio (m/m), dimensionless, the actual unit of K is $\mathrm{m}^3/\mathrm{m}^2/\mathrm{s}$. Hydraulic conductivity is an important property, it can be used to calculate corresponding flux from any hydraulic gradient.

"Intrinsic permeability" is a term used to describe the ability of a porous material to transmit fluid, but refers solely to the properties of the porous material. Sometimes "permeability" is used as a qualitative term, not quantitative. It indicates the ease of a media to transmit fluid. Difference between hydraulic conductivity and intrinsic permeability is described below (Table 4.8).

Table 4.8 Distinguishing features between hydraulic conductivity and intrinsic permeability

Hydraulic conductivity	Intrinsic permeability
It is the ratio of the flux to the hydraulic gradient, or slope of the flux versus gradient curve	It is used to describe the readiness with whichporous media transmit liquids
The hydraulic conductivity is not an exclusive property of the soil alone, since it depends on the attribute of the soil and of the fluid together	The permeability is ideally an exclusive property of the porous media alone
It is affected by both the soil texture and structure	It is affected only by the soil structure
Temperature dependent	Temperature independent
Fluid viscosity dependent	Independent of fluid viscosity

Factors Affecting Hydraulic Conductivity

Hydraulic conductivity is mainly affected by the following:

- Soil texture
- Structure
- Porosity
- Effective porosity/water-conducting pores (including cracks, root channels, worm holes, etc.)
- Soil grain size distribution and/or pore size distribution

Hydraulic conductivity varies spatially. For any given position in the field, the conductivity may vary with different soil layers. But the layer having lowest conductivity controls the final constant conductivity rate.

4.4.6.2 Measurement of Saturated Hydraulic Conductivity (K_{sat})

Field Measurement of K_{sat}

The determination of saturated hydraulic conductivity (K_{sat}) *in situ* is considered as most reliable and representative of actual field conditions. The methods developed for in situ determination of hydraulic conductivity may be grouped into two categories:

(1) Methods that are applicable to conditions having shallow water-table
(2) Methods that are applicable above the water-table or sites in the absence of water-table
(1) Determination of K_{sat} Within Water-Table

Available techniques in this category include the following:

(a) Auger-hole method (for unconfined water-table condition)
(b) Well-pumping method (under both confined and unconfined condition)

(a) Augar-Hole Method for Unconfined Water-Table Condition

This method is not applicable to confined aquifer and heterogeneous soil. This method provides an estimate of average horizontal (but not the vertical!) saturated hydraulic conductivity for the holed section within the aquifer. This method has many possible variations (Amoozegar and Warrick 1986). The principle and general procedure are outlined below.

Principle

A vertical hole is made upto certain depth below the water-table. After equilibrating the water level in the hole with the water-table, the water is pumped. The time required to refill the water-level to a certain level is recorded. The conductivity of the flowing soil-section is calculated using appropriate solution of the governing flow equation.

Tools Required

- Auger (any type, for boring the hole)
- Water-depth measuring device (meter scale, wooden scale, expandable measuring tap, or float-attached scale)
- Pumping device (having capacity consistence with the hole diameter and depth of water in the hole)
- Stop watch or digital watch

Working Method

- Select a representative location in the field (having less debris, crop root, and stone)
- Dug a hole up to 50 cm below the water level having diameter of 20~30 cm (care should be take to avoid smearing effect at the wall), clean the loose soil materials (Fig. 4.21)
- Wait until the water level in the hole stabilizes
- Pump the water fully from the hole, and record the time from the beginning of the refill of water
- Record the time required to reach the water level to a particular height/level, below the equilibrium water-table position (or alternately, measure the change in water level in a predetermined time period), and find the rate of rise
- Repeat the process for several times (3–5 times)
- Calculate the K_{sat} using the equation (solution for flow equation) given below

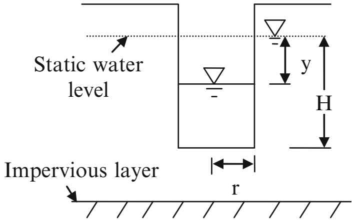


Fig. 4.21 Schematic of an auger-hole with definition of the elements

Solution of Governing Equation for Auger-Hole

Numerous solutions of flow system in bore-hole or auger-hole have been proposed. An approximate solution proposed by Ernst (cited by Amoozer and Warrick 1986) for auger-hole above an impervious layer is:

$$K_{\text{sat}} = \frac{4.63r^2}{y(H + 20r)(2 - y/H)} \cdot \frac{\Delta y}{\Delta t}, \tag{4.53}$$

where r is the radius of the hole (cm); H is the depth of stabilized groundwater level in the hole (cm); y is the difference between stabilized groundwater level (H) and the scheduled height of water level for rise-rate determination; $\Delta y/\Delta t$ is the change rate of y with respect to time, t; the K_{sat} has the same unit as of $\Delta y/\Delta t$.

The elements of the equation are shown in Fig. 4.21:

If the bottom of the hole is rest on impervious layer, the solution for K_{sat} is:

$$K_{\text{sat}} = \frac{4.17r^2}{y(H + 10r)(2 - y/H)} \frac{\Delta y}{\Delta t}. \tag{4.54}$$

Shortcoming/Limitations

Although the working method is simple and straightforward, it suffers from exact solution of the governing three-dimensional flow patterns near the hole or cavity. This method is applicable only where a cavity of known shape can be maintained throughout the test.

Precautions

- Smearing of the well walls can contribute to low K results, especially in clay-rich soil.
- Anisotropic conditions with greater hydraulic conductivity in the vertical direction can also affect the result.

(b) Well-Pumping Method

This is an enlarged form of auger-hole method. In this method, a vertical hole is constructed having reasonable diameter (50–100 cm). Water is withdrawn from the well instantaneously, and the recovery of the water level is measured with time.

This method provides an in-situ representation of horizontal saturated soil hydraulic conductivity having average over a larger representative volume of soil when compared with auger-hole or piezometer method.

(2) K_{sat} in the Absence of Water-Table (i.e., at Vadose Zone)

Field methods for determination of saturated hydraulic in the absence of water-table or far above the water-table are as follows:

- Bore-hole constant water level method
- Permeameter method

The bore-hole method is also referred to as "*constant head well permeameter method*" or "*dry auger-hole method.*" Numerous variations exist in the instrument and hence in the working procedure. But the principle is similar.

An apparatus named "*Constant-head permeameter*" has been designed by Amoozegar (Amoozegar 1989a, Amoozegar 1992). for measuring saturated hydraulic conductivity of the vadose zone. The apparatus maintains a constant height of water at the bottom of the hole, and measures the amount of water flowing into the hole. Any other type of tool that can maintain a constant water level in the well and can measure the flowing amount can be used in this method. Steady-state flow rate value under one constant head of water is required for calculating saturated hydraulic conductivity (K_{sat}). It is advisable to take measurement under different head and then average the K_{sat} value. The K_{sat} can be determined from the Glover solution:

$$K_{\text{sat}} = AQ, \tag{4.55}$$

where $A = [\sinh^{-1}(H/r) - \{(r/H)^2 + 1\}^{1/2} + r/H]/(2\pi H^2)$; Q is the steady-state rate of water flow from the permeameter into the auger hole; r is the radius of auger hole; H is the height of water level in the auger hole (constant height that is maintained in the permeameter); $\sinh^{-1}$is the hyperbolic sine function.

A brief discussion of glover solution can be found in Amoozegar (1992), Amoozegar (1989b). Definition sketch of elements of Glover solution is shown in Fig. 4.22.

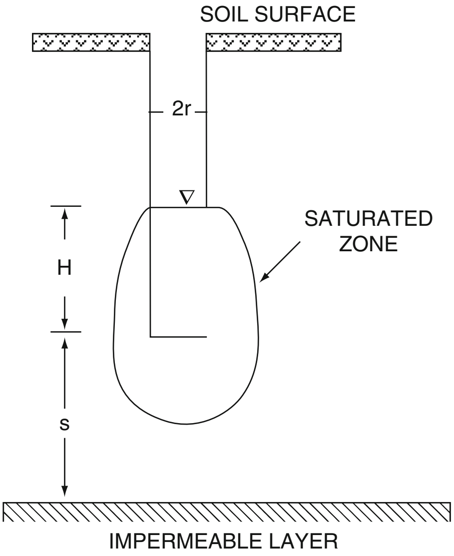


Fig. 4.22 Definition sketch of elements of Glover solution

If the distance between the bottom of the auger hole and any impermeable layer (s) is greater than $2H$, i.e., $s > 2H$, then the solution becomes:

$$K_{\mathrm{sat}} = BQ, \tag{4.56}$$

where $B = 3\ln(H/r)/\pi H(3H + 2s)$; $\ln(H/r)$ is the natural logarithm of H/r.

Working Method

Detail measurement procedure with Constant Head Well Permeameter is given below:

- The area is cleared from trash, plant materials.
- A 5-cm diameter hole is bored using auger. A hole cleaner (specially made by bending small spoon and attaching it with a small diameter steel rod) is to be used to withdraw the loose soil from bottom, and a brash may be used to reduce the smearing effect.
- The finished depth and radius of the hole are measured and recorded.
- Desired depth of water in the hole is maintained through differential mechanism of the instruments, and the depths H and h are measured. The rate of water flow (amount per unit time) is recorded.
- Before we can assume that a steady-state condition has been reached, three consecutive measurements in constant time interval (say 30 min) of the flow rate must be equal.
- After determining three consecutive steady-state flow rate, the depth of water in the hole is measured.
- Perform similar measurement for different depths of water in the hole, and average the K_{sat} values.

Laboratory Measurement of K_{sat}

Core Method

The soil core can be used to estimate the unsaturated hydraulic conductivity of a soil when field determination is not possible, or as a laboratory basis to compare other methods or theories. It is only an estimate of actual field conditions.

Soil samples are collected in cylindrical cores (brass, iron, or aluminium) of 3–5 cm height using an automatic (or manual) soil corer from required depths (0–90 cm for most practical purposes, and at 15-cm interval). Replicates of each depth are desirable. The cores are transported to the laboratory, and saturated in a vacuum chamber or in a saturated sand-box. The saturated hydraulic conductivity values are then determined using constant-head or falling-head method.

(a) Constant Head Method

Thr working procedure of this method is as follows:

- Cover the upper and lower end of the core sample with porous shed (or at least with cloth) and place it into the “constant head” apparatus

- Supply water from a regulated source (such as tap and/or with secondary control system)
- Maintain a constant water level (head) over the sample
- Place a beaker below the core to collect the drainage outflow/percolated water
- When a steady outflow will be established, start to collect the outflow and record the time
- Repeat the collection three times, and calculate the average
- Measure the length and diameter of the core
- Calculate the head difference and inner cross-sectional area of the core (area of outflow)
- Calculate the K_{sat} as given below:

$$v = ki, \qquad v = Q/A, \quad \text{thus } Q/A = ki$$

then,

$$K_{\mathrm{sat}} = VL/(At\Delta h) \tag{4.57}$$

where K_{sat} is in m/s, V is the volume of water drained through the sample in time t (m^3), L is the length of the soil sample (i.e., core) (m), A is the cross-sectional area of the soil sample (i.e., core) (m^2), t is the time in second, Δh is the head difference (m) = water head + half of core length

(b) Falling Head Method

In case of falling head, the final record of outflow and time are taken when the head over the sample becomes zero. Average water head is calculated from the initial and final head. Other procedures remain the same. In falling head technique, the flow through the soil column is unsteady-state flow. Thus, the head and discharge vary during the test. The conductivity is determined using the following equation:

$$K = \left(\frac{aL}{At}\right) \ln\left(\frac{H_1}{H_2}\right), \tag{4.58}$$

where a is the area of in-flow pipe (m^2), A is the area of soil column (m^2), L is the length of soil column (m), t is the time of flow (h), H_1 is the initial height of liquid (m), H_2 is the height of liquid after t hour (final height).

Major precautions for both the methods are related to proper sampling procedure, preparation of the specimen, and proper arrangement of circulating water. Disturbance of the soil structure results in nonrepresentation of field condition.

Other Instruments/Methods

Now-a-days, various instruments have been developed to measure the saturated hydraulic conductivity *in situ*, such as constant-head well permeameter, gulph permeameter, disk permeameter, etc. (e.g. Perroux and White, 1988). The new instruments have come with the manual detailing their operating procedures and theories associated with the principle. Saturated hydraulic conductivity of different soils is given below (Table 4.10).

4.4.6.3 Measurement of Unsaturated Hydraulic Conductivity (K_{unsat})

Unsaturated hydraulic conductivity is a measure of how water flows through a soil profile when the soil is not saturated with water. The unsaturated hydraulic conductivity of a soil is important when evaluating the movement of nutrients and pesticides through the soil at different water contents. In some text, the term "unsaturated hydraulic conductivity" is referred to as "capillary conductivity", and the term "hydraulic conductivity" is reserved for saturated flow.

Flow of water in unsaturated porous media is particularly complex and mathematical description is difficult. Exploitation of numerical methods of analysis and modern rapid computational procedures now allow application of theoretical principles of flow to more complex systems. The necessity of having a satisfactory description of the hydraulic conductivity – water content or suction relation, and the water content – suction relation for such homogeneous soil volume in the system has been a major deterrent.

Commonly used methods for measuring unsaturated hydraulic conductivity are given below:

(a) Instantaneous profile method
(b) Internal drainage method
(c) Saturating unsaturated soil core or column

Instantaneous Profile Method

The instantaneous profile method for determining unsaturated hydraulic conductivity and diffusivity is based on Darcian analysis of transient soil water content and hydraulic head profiles during vertical drainage following a thorough wetting by irrigation or rain.

Richards et al. (1956) was the first to use the drainage flux method in the field. Waston (1966) improved upon the method by replacing the computation of differences in time and depth by the presumably more accurate "instantaneous profile method" in laboratory studies. The instantaneous profile method was then adapted to the field (Hillel et al. 1972; van Bavel et al. 1968).

The method requires monitoring the transient state internal drainage of a soil profile. Uniform, one-dimensional flow, non-hysteric, and isothermal conditions are assumed, enabling the use of a Darcian analysis of vertical drainage described by:

$$\frac{\partial \theta}{\partial t}=\frac{\partial}{\partial z}\left[K(\theta)\frac{\partial H(z,t)}{\partial z}\right], \tag{4.59}$$

where $K(\theta)$ is the hydraulic conductivity as a function of soil wetness (m s^{-1}), $H=$ hydraulic head (m) $= \psi + z$; ψ(m) is the matric potential, and z is the depth (m) positive downward.

Frequent and concurrent measurements of both the soil wetness and matric suction over time are required during vertical drainage of a uniformly wet soil profile. From these measurements, the unsaturated hydraulic conductivity and diffusivity as well as the water content and hydraulic head profiles can be determined.

The instantaneous profile method may be conducted in a small (1.5 m × 1.5 m, or 2.0 m × 2.0 m) area. The soil profile should be saturated, and then the soil surface is to be covered with plastic or polythene (and a layer of sand over it) to prevent evaporation. Measurements of the soil moisture and matric potential are to be made with TDR or depth moisture gauge (DMG) and tensiometer, respectively, at 15–30 cm increments to a depth of about 100–160 cm. If TDR or DMG is not available, gravimetric determination of moisture using soil cores may be accomplished.

The method can be limited by the properties of the soil being tested as well as the assumptions inherent in the theory. The method works well when applied to field situations where a water-table may be absent or too deep to affect soil moisture flow and where the soil profile is either homogeneous or heterogeneous with layered. However, it will not work well in slopping or slowly permeable soils where lateral flow would no longer be negligible. Although used in the field and presumed to be representative of an area, it only measures the hydraulic properties of the soil in one direction, downward. The method is also limited in its range of application, it can only measure properties between saturated and field capacity conditions (after which water movement may be too slow to detect).

Internal Drainage Method

The general equation describing the flow of water in a vertical soil profile is:

$$\frac{\partial \theta}{\partial t}=\frac{\partial}{\partial z}\left[K(\theta)\frac{\partial H(z,t)}{\partial z}\right]$$

By integrating, we obtain

$$\int_0^z \frac{\partial \theta}{\partial t} z = \left[K\frac{\partial H}{\partial z}\right]_z$$

or

$$\frac{\partial \theta}{\partial t} z = \left[K \frac{\partial H}{\partial z} \right]_z .$$

Here, z is the soil depth to which the measurement applies.

If the soil surface is covered to prevent evaporation and only internal drainage is allowed, the total water content change per unit time (obtained by integrating between successive soil moisture profiles down to depth z) is thus

$$\left(\frac{\partial w}{\partial t} \right)_z = K \left(\frac{\partial H}{\partial z} \right)_z = q$$

Here W is the total water content of the profile to depth z, i.e.

$$W = \int_0^z \theta \mathrm{d}z$$

Finally

$$K(\theta) = \frac{q}{\partial H / \partial z} . \tag{4.60}$$

During the internal drainage of a deeply wetted profile, $(\delta H/\delta z)_z$ (the hydraulic gradient at depth z) is often found to be unity. That is, the suction gradient is nil and only the gravitational gradient operates. If so, then

$$k = (\mathrm{d}w/\mathrm{d}t)_z .$$

Otherwise, the suction gradient must be taken into account and hydraulic conductivity is obtained from the ratio of flux to the total hydraulic gradient (gravitational plus matric).

This can be done successively at gradually diminishing water content during drainage, to obtain a series of K vs. θ values and thus establish the functional dependence of hydraulic conductivity upon soil wetness for each layer in the profile.

Working procedure for in situ measurement

To apply this method, one must choose a representative fallow plot that is large enough (i.e., 4.0 m × 4.0 m) so that processes at its center are unaffected by its boundaries. Within the plot, at least one neutron access tube must be installed as deeply as possible to below the root zone. The required depth usually exceeds 1.2 m. A series of tensiometers are installed near the access tube (far enough to avoid interfering with the neutron reading, yet near enough to monitor the same

Table 4.9 Distinguishing characteristics of flow velocity and Darcian flux

Flow velocity	Darcian flux or flux density
Flow does not take place through the entire cross-sectional area	Flow is assumed to take place through the entire cross-sectional area
The mean flow velocity through the soil pore is given by the ratio of flux to volumetric soil-water content	The Darcian flux or flux density is the volume of water passing through a unit cross-sectional area per unit time
Mathematically it can be expressed as $v = q/\theta$	Mathematically it can be expressed as $q = Q/A = Ki/A = K\Delta h/AL$
Flow velocity is always greater than the flux	Flux is always smaller than flow velocity

Table 4.10 Typical saturated hydraulic conductivity values of major soil classes

Soil type	K_{sat} range (mm/day)
Heavy clay soil	2–4
Clay soil	2–6
Loam soil	5–10
Sandy soil	10–15

soil mass, a distance of 50 cm), at intervals not exceeding 30 cm, to a depth as great as possible. Water is then ponded on the surface (long enough so that the entire profile becomes as wet as it can be. Tensiometer readings can indicate (zero reading) when steady-state infiltration conditions have been achieved. When the irrigation is deemed sufficient, the plot is covered by a sheet of plastic so as to prevent any water flux across the surface (evaporation). To minimize thermal effects, an impervious surface can be painted while at least covered with a layer of loose soil. As the internal drainage process proceeds, periodic measurements are made of water content and tension throughout the profile. The reading must be taken frequently at first (one to thrice a day) but can be taken at greater time intervals as the internal drainage process slows down.

Data processing

- Plot the volumetric moisture content variation with time for each depth.
- Calculate soil moisture flux through each increment by integrating moisture-time curve with respect to depth [$q = \Sigma \mathrm{d}z(\mathrm{d}\theta/\mathrm{d}z)$].
- Plot moisture suction variation with time for each depth.
- Calculate and plot hydraulic head profiles by adding matric suction to depth for each depth.
- Calculate hydraulic conductivity at each depth and for different moisture contents by dividing fluxes by the corresponding hydraulic gradient values. The gradients are obtained by measuring the slopes of hydraulic head vs. soil depth graph.
- Plot hydraulic conductivity against volumetric moisture content (in a semi-log paper, i.e., log$K$ vs. θ and draw best-fit curves for the different layers.

- Check whether the entire profile can be characterized by a single curve.
- Calculate functional dependence of K upon θ

By Saturating Unsaturated Soil Core or Column

Unsaturated hydraulic conductivity may be determined by controlling inflow rate in an unsaturated soil and recording the time to reach water to the other end. In this approach, core sample of soil is collected just as of saturated hydraulic conductivity determination. Then the water content of the soil is reduced to a certain water content (such as of 1, 3, 5, or 10 bar). Water is then applied to the bottom of the column of soil at a constant but slow rate. The time taken for the water to reach the top of the soil column is recorded. The time required for water to fill the column is then used to calculate the unsaturated hydraulic conductivity of that soil. The procedure is repeated with different length of soil column and different initial soil water contents. The average of different settings will give a reliable estimate of the unsaturated hydraulic conductivity.

To provide a uniform soil water content of the soil column, the sample may be saturated first, and then dried up. A tensiometer may be mounted at the top of the column of the soil connecting with computer to record the changes in tensiometer, and thereby exact time to reach the water at the end of column.

Indirect estimation of K_{unsat} *from saturated hydraulic conductivity value*

Unsaturated hydraulic conductivity can be estimated from saturated conductivity value as (van Genuchten et al. 1980):

$$K(h) = K_{\text{s}} \frac{1 - (\alpha h)^{n-2}[1 + (\alpha h)^n]^{-m}}{\{1 + (\alpha h)^n\}^{2m}}, \tag{4.61}$$

where K_{s} is the saturated hydraulic conductivity (cm/s), h is the soil water tension (cm), $K(h)$ is the unsaturated hydraulic conductivity at tension (h, cm/s), and α, n, m are parameters that should be determined by fitting the soil water retention data (of the same soil) to the following empirical model of van Genuchten et al. (1980):

$$\theta = \theta_{\text{r}} + \frac{\theta_{\text{s}} - \theta_{\text{r}}}{[1 + (\alpha h)^n]^m}, \tag{4.62}$$

where θ_{r} and θ_{s} refers to the residual and saturated volumetric water contents, respectively; h is the soil water tension; and α, n, m are parameters that determine the shape of the curve.

4.4.7 Swelling and Shrinkage Properties of Soil

4.4.7.1 Concept of Swelling and Shrinkage, and Extent of Cracking Clay Soil

Moisture changes in swelling clays lead to corresponding volume changes, causing these soils to swell upon wetting and shrink upon drying. These soils can shrink or swell in the vertical as well as horizontal direction. Volume changes in the vertical result in subsidence, whereas horizontal volume changes result in crack formation.

Cracking clay soils (vertisols) have physical properties that set them uniquely from the vast arrow of soils mantling the global landscape. Vertisols occupy approximately 1.8% of the world's land area (Donahue et al. 1977) and are widely distributed between 45° north and south latitudes. Although vertisols cover a small part of the world's surface, they are important in semi-arid agriculture because, in this environment, they are among the most productive soils.

4.4.7.2 General Properties and Behavior of Cracking Clay Soil

The common cardinal profile features of these soils are extensive cracking from the surface to depths of 50 cm or more with seasonal drying. Also, there is a considerable range in surface condition, which affects water entry and agricultural use. These include both fine- and coarse-structured, self-mulching surfaces as well as those with massive surface crusts of 2–6 cm thick. Many of the common features are directly associated with the high amounts of clay present, its mineralogy, and the composition of adsorbed cations. Such features include their potential for swelling and shrinking, hard or sticky consistence, relatively high soil water content at both 15 and 0.1 bar suction, very low saturated hydraulic conductivity, relatively high base status, and carbon retention in the root zone.

The most important attribute of these soils is the cracking phenomenon, which affects water distribution in the profile and hence the behavior of numerous assessory characteristics (e.g., infiltration and aeration, change in bulk density with water content, the effect of stress potential on the moisture characteristics), which the moisture regime interacts. Although vertisols can store large quantities of water because of their high clay content and swelling properties, their -15 bar water content is high. This can cause problems in plants obtaining water during periods of light rainfall.

4.4.7.3 Shrinkage Curve

The volume changes of clay soils are conveniently described by a shrinkage characteristic curve that describes the relationship between void ratio (ratio of volume of voids to volume of solids) and moisture ratio (ratio of volume of moisture to volume of voids). Sometimes, it is expressed as the relation between specific volume (reciprocal of bulk density) against gravimetric water content.

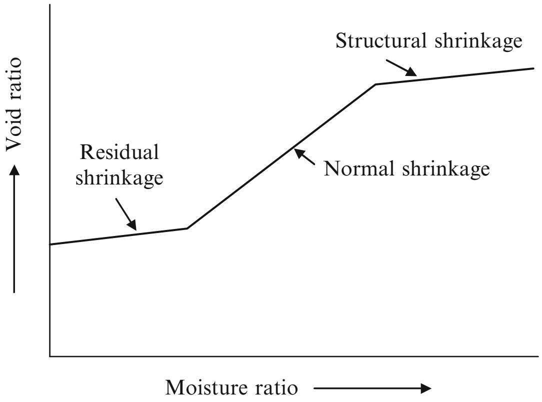


Fig. 4.23 Typical shrinkage curve of vertisols

Most vertisols have a shrinkage curve similar to that shown in Fig. 4.23 (Ali 2000). Three zones are apparent. There is a “structural” zone at the wet end and a “residual” zone at the dry end, where the volumetric change is smaller than the volume of water lost or gained. Between them is the “normal” zone where the volume change is equal to the volume of water lost or gained (slope $= 1$). The normal zone extends over the range of water potentials -0.3 to < -15 bars that is agriculturally important for plant growth.

4.4.7.4 Problems with Cracking Clay Soil in Relation to Water Management

In general, vertisols have much reduced hydraulic conductivity in the swollen state, so that both infiltration and internal drainage are very slow. This results in poor aeration of wet soils and retards root development. Under natural rainfall, the infiltration behavior in a vertisol is not simple. If the rainfall rate exceeds the infiltration rate, the water infiltrates through the crack walls. Thus the rainfall pattern, cracking pattern, rate of crack and surface mulch conditions become important.

Flow of water and solutes in cracking clay is quite different from flow in more sandy or loamy soils in which most soil pores in the soil matrix contribute to water movement. Dunne and Diertrich (1980) have shown that infiltration into clay soils is controlled by the degree of development of cracks and the evolution of cracks after rain. Many heavy clay soils have relatively large cracks, which occur in a fine-porous soil matrix. This matrix has both very low hydraulic conductivity and sorptivity and significant fluxes of water and solute through the entire soil, which is therefore only possible when continuous large pores are present. These large pores are unstable as their dimensions change upon swelling and shrinking of the soil following wetting and drying. A particularly complex condition is observed when free water infiltrates along vertical cracks into an unsaturated soil matrix. Water moves downward rapidly through initially air-field large, vertical pores, thereby bypassing dry or moist soil inside the peds. Such processes have widely been observed in the field and the name "short-circuiting," "channeling flow," "preferential flow," or "bypass flow" have been used to describe the phenomenon (Bouma et al. 1978, Beven 1982). Water infiltrates from top of the soil, as well as from the water-field cracks. Swelling and shrinkage phenomena influence infiltration in such a soil.

4.4.7.5 Problems of Applying General Approaches to Describe/Simulate Water Flow in Cracking Clay Soil

In the absence of a continuous macro-pore network, water flow in a homogeneous, non-macroporous soil obeys the classical water flow theory based on the Backingham-Darcy law. However, when cracks are present this theory may not adequately describe the infiltration and redistribution of water. Although these cracks may comprise only a small fraction of the total soil volume, they can have a profound effect on the rate of infiltration and redistribution of water depending on the amount of water supply to the soil surface, the initial moisture content of the soil matrix, the micro-relief of the surface, etc. As a result, pollutants dissolved in water can reach deeper soil layers, and ground water table may rise much faster than could be expected assuming homogeneous flow in the matrix.

The Richard's equation is commonly used to describe water flow in homogenous soils. However, when cracks are present, the one-domain approach is no longer a reliable modeling approach because two kinds of flow types can occur in one medium. The one-domain approach has nothing particular to say about preferred flow along cracks and assumes that if the soil is unsaturated, the larger voids will not conduct water.

4.4.7.6 Determination of Shrinkage Characteristics

The shrinkage characteristic curve is obtained by simultaneously determining the volume of voids and the volume of water contained in a known volume of solids over the whole range of moisture contents (i.e., fully saturated and swollen state to oven-dry and fully contracted state).

The bulk soil weight and volume can be determined by measuring the weight and the volume of fluid displaced by the soil specimen. Kerosene, paraffin, saran coating, and rubber balloon method have been used for shrinkage measurement.

In the balloon method, errors are associated with entrapped air and with the dependence of the fit of the balloon. As a coating material, "Saran" (copolymer of vinylidence chloride and acrylonitrile) has several advantages over paraffin. It does not melt at 105°C – volume can be determined after oven-drying; it is flexible – the coating adheres to a clod and contracts or expands as the cold expands or swells. The saran coating is permeable to water vapor, permitting a clod to gain or lose water, but is practically impermeable to liquid water, permitting volume measurements by displacement of water. The problem is that it is hazardous chemical and requires centrifuge and air exhaust system.

Balloon Method

This method does not require the use of any toxic chemicals. The soil specimen is separated from the water by a thin flexible layer, using an ordinary rubber balloon. A small soil clod, about 50–80 cm^3 in volume, is placed inside the rubber balloon. Then soil volume is then determined by measuring the displacement of the water by the soil specimen. After control drying of soil clod in the oven, the volume is determined in the same way. For large samples or natural clods, the sample may be placed inside the balloon using a suction cylinder.

Saran Resin Method

Saran resin can be used to coat the soil clod, and then the volume change of the clod can be measured (Brasher et al. 1966; Ali and Tural 2000).

Principle of Saran Resin Method

The coated clods are weighed in air and in water to determine mass and volume. The volume change, change in total porosity, change in void ratio and moisture ratio can be calculated from these measurements.

Detail working method

- Dow “Saran resin” is dissolved in methyl ketone in the ratio of 1:4 resin/solvent. Until dissolved, the mixture is stirred with a wooden stick under exhaust hood.
- The clod is tied and immerged by fine rope in the saran solution for about 5–10 s.
- It is then taken out of the solution, hung upto dry, which usually requires 15–30 min.
- A patch of saran coating is removed from a relatively flat surface. The exposed area is covered with nylon cloth and placed in firm contact with a tension table *or* saturated sand box, which is equilibrated at 4.5 cm water tension.
- After 3–5 days, the clods are removed and the exposed surface is recoated with saran.
- After drying the coated surface, the samples are weighed first in air (placing over an electronic balance), and then in water with an electronic balance that can accept the clod hanging on the beam, to determine the volume by Archimedes’ principle. The temperature of water is recorded to determine the density of water.

As an alternative of such hanging balance, the clods can be immerged in a calibrated (i.e., marked) bucket/cylinder containing water. The change in water volume due to insertion of clod is the volume of the clod.

- Then clods are put in oven for drying (with the aim of reducing some moisture, at 40–60°C for several hours).
- After each oven dry treatment, the clods are reweighed in air and water (to find out the change in moisture and volume). The temperature of water is recorded for each case.
- Finally, the clod is dried in oven at 105°C.

Data sheet and calculation of shrinkage data

(a) Data of first dry-treatment

Sample ID no.	Wt. in air (gm) (1)	Wt. in water (gm) (2)	Wt. loss in water (wt. of displaced water) (1)–(2) (3)	Density of water at measured temp. (gm/cc) (4)	Vol. of displaced water (= vol. of soil clod) (3)÷(4) (5)	Wt. in air after 1st dry (gm) (6)	Wt. in water after 1st dry (gm) (7)
1	545.5	240.5	305.0	1.0	305.6	515.2	215.6
2							

Note: wt. in air and water after first dry-treatment is the initial wt. in air and water for the second dry-treatment

(b) Data after final oven-dry *(continuation of sheet (a))*

Sample ID no.	Wt. in air after final oven-dry (gm) (8)	Wt. in water after final oven-dry (gm) (9)	Water in sample at measurement point (gm) (1)–(8) (10)	Vol. of water at that point (10)/ρ (11)	Correction for saran coating[a] (gm) (12)	Wt of solid (8)–(12) (13)	Vol. of solid (13)/ 2.65 (14)	Vol. of pore (5)–(14) (15)	Void ratio (15)/ ((14) (16)	Moisture ratio (11)/ (13) (17)
1	435.18	189.6								

Note: ρ density of water at that temperature

[a] Correction for saran coating is determined as follows:
Vol. of a circular mass, $V = (4/3)\pi r^3$
or $r = (3V/4\pi)^{1/3}$
Wt. of coating $= 2\pi r h \times$ (density of coating)
where, h = thickness of coating ($\approx$0.3 mm), and density of coating = 1.3 gm/cc

4.4.7.7 Functional Form of Swelling and Shrinkage

Geometry of Shrinkage

The geometry of shrinkage of a saturated clay soil cube with size z (m) can be described by a dimensionless geometry factor r_s (Bronswijk 1988):

$$\left(1-\frac{\Delta V_1}{V_1}\right)=\left(1-\frac{\Delta z}{z}\right)^{r_s}, \tag{4.63}$$

where V_1 is the volume of soil matrix at saturation (m^3), Z is the layer thickness of a soil cube with volume V_1 at saturation (m), ΔV_1 is the decrease in volume of the soil matrix a result of shrinkage (m^3), Δz is the decrease in layer thickness at a result of shrinkage (m), r_s is the dimensionless geometry factor (for three-dimensional isotropic shrinkage, $r_s = 3$, for one-dimensional subsidence, $r_s= 1$).

From the above equation, three-dimensional volume change (ΔV_1) can be estimated from the known value of r_s and measured vertical change in layer thickness (Δz), as:

$$\Delta V_1=\left[1-\left(1-\frac{\Delta z}{z}\right)^{r_s}\right]z^3. \tag{4.64}$$

Logistic Model of Shrinkage Characteristics

The basic shape of many of the published data sets of soil shrinkage is that of an "*S*" shaped curve with a gradual flattening of the relationship at two ends and with a relatively straight section between them (corresponding to the normal shrinkage zone). This type of shape suggests that sigmoidal growth curve should provide a reasonable good approximation.

The generalized mathematic form of logistic curve is (Nelder 1962; Mcgarry and Malafant 1987):

$$y=a+\frac{c}{\{1+t\exp[-b(x-m)]\}^{1/t}}, \tag{4.65}$$

where a is the lower asymptote, $x = m$ is the point of inflection, b is the slope parameter, t is the power law parameter with ($a + c$) is the upper asymptote.

Simplest form of the logistic model assumed that $t = 1$ and leads to the logistic equation:

$$y=a+\frac{c}{1+\exp[-b(x-m)]}. \tag{4.66}$$

4.4.8 Biological Properties of Soil

4.4.8.1 Concept

Soil scientists measure soil biological health in terms of microbial biomass, microbial communities, and rate of organic matter decomposition. Soil contains a large array of life forms, from large soil animals (e.g., earthworm) to micro-organisms (e.g., bacteria). There are huge organisms in a teaspoon of agricultural soil. Decomposition of plant and animal residues (into organic matter) is a biological process involving a variety of soil organisms, including beetles and other insects, worms, nematodes, fungi, algae, and bacteria. They cause denitrification, fix atmospheric nitrogen, etc. Soil microbial biomass is defined as the living part of the soil organic matter, excluding plant roots and soil animals larger than $5 \times 10^3 \mu m^3$.

4.4.8.2 Classification of Soil Organisms

Soil organisms may be broadly classified into macro- and micro-organisms. The living soil organisms' population is dominated by the micro-organism (~60–80%). Among the macro-group, earthworm and arthropods are prominent. Among the micro-group, algae, fungi, nematodes, and bacteria are prominent. Some organisms such as nematodes and fungi are harmful, while others are beneficial.

4.4.8.3 Beneficial Effects of Soil Organisms

Soil organisms are involved in various transformations of plant nutrient elements. When ammonium fertilizer is applied in soil, bacteria convert the ammonium-N to nitrite-N. Similarly, when elemental sulfur is applied, bacteria convert it to sulfuric acid, which lowers soil pH. *Rhizobia* bacterium that forms nodules on the roots of legumes transforms atmospheric nitrogen into nitrogen available for plant use.

4.4.8.4 Factors Affecting Organism Populations

Management and crop rotation/vegetation. Soil microbial biomass and biological properties vary with different management and crop rotation systems. Soil biological properties in urban environments differ from those in other managed and natural systems.

Climate/Temperature/Moisture. Microbes vary with respect to dryness or wet condition, more with moist soil. The population is higher near the soil surface where moisture, temperature, aeration, and food supply are the highest.

Human activities. If crop residues are burned in the field, the microbes may be destroyed. Sometimes, it is burned to kill the harmful nematodes.

Food for organisms. Sufficient food for organisms accelerates their growth. To build or maintain soil biological quality, we should adopt soil management practices that provide soil organisms with food, air, water, and other necessary conditions for their growth and reproduction.

4.4.9 Improvement of Soil Physical, Chemical, and Biological Properties

4.4.9.1 Soil or Land Degradation

Among the soil forming factors, time plays the most significant role in soil physical, chemical, and biological difference. Soil or land degradation can be defined as the loss of utility through reduction of or damage to physical, chemical, biological, or economic features and/or ecosystem diversity. The proximate causes of nutrient depletion are very low use of inorganic fertilizers and limited use of organic inputs coupled with declining fallow periods. The proximate causes of soil erosion are deforestation and crop production on steep slopes with limited investments in terraces or other conservation measures.

Soil can become contaminated if harmful substances are:

- Applied as components of other allowed materials (e.g., compost, other organic and inorganic compounds)
- Contained in seed coating
- Contained in irrigation water

Several factors such as policies, technologies, institutions, population pressure, and agro-climatic conditions can affect soil sustainability and agricultural growth.

4.4.9.2 Monitoring Indicators of Different Properties

For better management of soil and to improve soil properties, we should know the soil characteristics associated with improved physical, chemical, and biological conditions. These will help in undertaking management practices that can facilitate these changes.

A soil can be regarded as having good physical conditions by the following characteristics:

- The soil is porous, not tightly packed.
- Plant roots can grow through the soil without restriction.
- Water, plant nutrients, and air (needed by plants and soil organisms) can move through the soil with relative ease.
- Irrigation water or water from rainfall infiltrates into the soil, rather than flowing over the soil surface as runoff.
- Soil can hold sufficient water obtained from rain or irrigation.
- Soil organisms (involves in decomposition and mineralization of plant and animal residues) are able to thrive and disperse throughout the soil.

We can evaluate a soil for good chemical conditions by monitoring the following characteristics:

- The soil has a near-neutral pH
- Sufficient plant nutrients are available for crop growth, but not in toxic amount
- The soil does not contain any heavy metal or other toxic element
- Soil nutrients are in available form for plant uptake

- The soil contains sufficient organic mater, which helps to hold water and nutrients
- The soil contains sufficient oxygen for plant growth and growth of organisms

We can evaluate a soil for healthy biological conditions by monitoring the following characteristics:

- Legumes form abundant healthy nodules (and abundant nitrogen), especially in nitrogen-depleted soil
- Crop residues and manure added to the soil are decomposed relatively quickly
- Soil organisms such as earthworm, dung beetles, and springtails are present
- Soil has good tilth and is well-aggregated
- A good soil structure, provided by stable organic compounds, remains following the decomposition of plant and animal materials
- The soil smells "sweet" and "earthy"

4.4.9.3 Means of Improvement of Different Properties

Improvement of Soil Physical Properties

Soil physical properties (bulk density, porosity, water holding capacity, etc.) can be improved through the following measures:

- Addition of organic matter (may be of both plant and animal origin)
- Application of bio-fertilizer
- Application of green manure/crop residue/compost fertilizer
- Appropriate tillage operation (tillage practice that minimize degradation of soil aggregates, minimally disrupt the habitat of beneficial soil organisms)
- Application of sand, rice husk, wooden dust, etc. in heavy clay soil
- Maintenance of proper drainage system and appropriate moisture condition

Organic matter improves soil structure, reduces crusting and compaction. It increases water-holding capacity. Yearly or periodical addition of organic matter is necessary for the maintenance of soil in good health and fertility.

Improvement of Soil Chemical Properties

Soil chemical properties (pH, CEC, EC, available nutrients, exchangeable cations, organic carbon, etc.) can be improved through:

- Application of organic matter
- Application of gypsum in sodic and saline soil
- Maintaining the soil pH near neutral (i.e., application of lime in acidic soil)
- Facilitating proper drainage in water-logged soil
- Correction of soil mineral deficiencies (i.e., supply correct doses of plant macro- and micro-nutrients).
- Organic farming

Organic matter buffers the soil against rapid changes in acidity, alkalinity, and salinity. It increases cation exchange capacity of soil.

Improvement of Soil Biological Properties

Soil biological properties can be improved through:

- Addition of organic matter or plant and animal residues as food and energy sources for soil organisms
- Application of bio-fertilizer
- Correction of soil pH (if needed)
- Cultivation of leguminous crop
- Providing well drainage condition
- Tillage operation, mulch tillage or otherwise mulching with organic materials
- Maintaining the soil moist to provide favorable environment for the microbes
- Avoiding soil heating or burning crop residues in the field
- Organic farming

4.4.9.4 Organic Farming

Organic farming is a method of farming that avoids or largely excludes the use of harmful chemicals such as chemical fertilizers, pesticides, and herbicides, and includes the use of natural organic resources such as organic fertilizer, mineral, organic pesticides, and microbes (bio-fertilizer) to main the environment (water, soil, air) free from pollution and to provide stability to the production level. Organic farming system relies on large scale application of FYM or animal wastes, compost, green manure, crop residues, vermicompost, bio-fertilizer, and biological control. Organic farming leads to live in harmony with nature. Organic agriculture is the key to a sound agricultural development and a sustainable environment.

To make organic farming successful, it is essential that eco-friendly technologies, which can maintain soil health and increase crop productivity, have to be developed.

Relevant Journals

- Soil Science
- Soil Science Society of America Journal
- Australian Journal of Soil Research
- European Journal of Soil Research
- Indian Journal of Soil Science
- Journal of Soil Science
- Soil and Tillage Research
- Vadose Zone Journal
- Geoderma
- Transport in Porous Media
- Journal of Hydrology
- Hydrological Processes
- Soil Biology and Biochemistry
- Agronomy Journal

FAO Soil Bulletins

- FAO Soil Bulletin 8: Soil Survey Interpretation and Its Use
- FAO Soil Bulletin 10: Physical and Chemical Methods of Soil and Water Analysis
- FAO Soil Bulletin 42: Soil Survey Investigation for Irrigation
- FAO Soil Bulletin 29: Land Evaluation in Europe
- FAO Soil Bulletin 33: Soil Conservation and Management in Developing Countries
- FAO Soil Bulletin 58: Nature and Management of Tropical Peat Soil
- FAO Soil Bulletin 35: Organic Material and Soil Productivity
- FAO Soil Bulletin 25: Sandy Soils
- FAO Soil Bulletin 34: Assessing Soil Degradation

Questions

1. What are the importances of soil properties for an irrigation engineer?
2. Define agricultural soil. What are the components of soil?
3. Briefly discuss the physical properties of soil.
4. What do you mean by soil bulk density? What are the factors affecting soil bulk density? Draw a sketch of soil bulk density with depth.
5. Discuss various direct methods of determining soil bulk density. Narrate their relative merits and demerits.
6. Write short note on: soil texture, soil particle density
7. Discuss various soil physical and hydraulic properties of different textured soils.
8. Is it possible to modify the soil texture?
9. Briefly narrate one method for analyzing particle size of soil.
10. Write short on: (a) soil structure, (b) porosity, (c) void ratio
11. Write down the equation relating bulk density, particle density, and porosity.
12. What is the importance of soil physical properties in irrigation and drainage activities?
13. What is infiltration? Briefly discuss its importance in irrigation and water management.
14. Draw a typical infiltration curve. Discuss the factors influencing infiltration.
15. Describe Darcy's and Richards' equation in water movement. What are the assumptions in Richards' equation?
16. Write down the equation for horizontal infiltration.
17. What is Darcian flux?
18. Briefly narrate the Philip's and Swartzendruber's solution of Richards' equation.
19. Define the (a) Green and Ampt, (b) Horton's, (c) Collis-George, and (d) Kostiakov equation for infiltration.
20. Discuss the procedure for measuring infiltration using (a) single ring, and (b) double ring infiltrometer.
21. What do you mean by soil pH? What are the sources of H^+in the soil?

22. What do you mean by cation exchange capacity (CEC) of soil? Write down its importance.
23. Define soil water. What are the factors affecting soil water?
24. Describe the procedure for direct measurement of soil water.
25. Briefly discuss various indirect methods of measuring soil moisture. Narrate their relative advantages and disadvantages.
26. What are the components of soil water potential?
27. What is the importance of soil hydraulic property in irrigation management?
28. Define and describe the procedure for determining the following soil-water constants: (a) Saturation capacity, (b) Field capacity (FC), (c) Wilting point (WP)
29. What is soil-moisture characteristic curve?
30. Discuss various methods of determining moisture at low tension.
31. Briefly describe the principle and working method of determining moisture at high tension by pressure plate apparatus.
32. Describe various soil-water functions/models.
33. What is hysteresis? What are the factors affecting hysteresis in soil-water retention? Draw a sketch showing hysteresis.
34. Define soil water diffusivity.
35. What are the various types of flow of water through soil?
36. Define "hydraulic conductivity" and "intrinsic permeability." What are the factors influencing hydraulic conductivity of soil?
37. Distinguish between: (a) "hydraulic conductivity" and "intrinsic permeability", (b) "flow velocity" and "Darcian flux."
38. Describe various field and laboratory methods for determining (a) saturated hydraulic conductivity (K_{sat}), (b) unsaturated hydraulic conductivity (K_{unsat}).
39. Describe van Genuchten function for estimating unsaturated hydraulic conductivity.
40. Define swelling and shrinkage of soil. Describe the properties of cracking clay soil.
41. Sketch the typical shrinkage curve of vertisol.
42. What are the problems of cracking clay soil in relation to water management?
43. Describe a method for determining shrinkage characteristics of soil.
44. Describe the function for (a) geometry of shrinkage, and (b) logistic curve.
45. Discuss the ways and means for improvement of soil physical, chemical, hydraulic, and biological properties of soil.

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Chapter 5
Plant: A Machinery of Water Absorption

Among the living organisms, only the green plants are able to build up organic food from the relatively raw materials of the inorganic world. Plants are not limited by size because of their indeterminate growth and architectural design. This gives plants the ability to colonize and exploit new areas for resources. Growing conditions and management decisions at any stage of crop plant can have a significant bearing on the ultimate performance of the crop. In modeling water and nutrient uptake and in quantifying the effect of fertilizer and/or irrigation on growth and yield, root information is needed because root is the organ of the plant which takes up necessary nutrient and water for the plant.

Water is a reactant in many chemical reactions in the plant. Water movement from cell to cell in plants occurs along gradients of “water potential”. Water-related data of plants in different environments facilitate understanding about how plants “adjust or adapt” in order to maintain an appropriate water status that is necessary for survival and growth. The overall ability of a plant to survive in a drought condition depends on many morphological, physiological, and phenological characteristics. A sound understanding of plant growth and development, morpho-physiological structure, and plant–water relations is essential for efficient and economic crop management.

5.1 General Overview and Types of Plant

5.1.1 General Overview

Plants have an architectural design. In other words, the plant body is constructed like a building – modular. It is built of a limited number of units, each of which is relatively independent of the others and that are united into a single structure. Thus, just like a building is made of rooms, the leaves, stems, and roots of a plant are analogous to rooms in the building. Each room is somewhat independent, yet they all function together to make an integrated whole. You can seal off a room in a

M.H. Ali, *Fundamentals of Irrigation and On-farm Water Management: Volume 1*,
DOI 10.1007/978-1-4419-6335-2_5,

building, or remove a leaf or fruit, with little harm to the overall integrity of the structure. This is critical for plants to be able to add or remove parts (leaves, stems, flowers, fruits) as necessary. Plants are not limited by size because of their indeterminate growth and architectural design. This gives plants the ability to colonize and exploit new areas for resources.

Among the living organisms, only the green plants are able to build up organic food from the relatively raw materials of the inorganic world. (Certain bacteria, e.g., nitrifying and sulfur bacteria, are also able to build up organic materials. They obtain their energy by oxidizing ammonia and hydrogen sulfide and obtain carbon from the carbon dioxide of the air without the agency of sunlight. The organic substances produced are relatively negligible in amount.) The plant in its botanical sense includes every being which has vegetative-life, from the loftiest tree which adorns our landscapes to the humblest moss which grows on its stem, to the mould or fungus which attacks out provisions, or the green scum that floats on our ponds.

Information on crop characteristics is required to determine plant's available soil-water. Crop rooting pattern, the depth of rooting, density of roots with depth, and crop susceptibility to water stress are important crop characteristics.

5.1.2 Types of Plants

Plants can be classified in various ways. Several classes of plants are presented here. In a broad sense, plants may be classified into monocarpic and caulocarpic.

Monocarpic: These type of plants die after one flowering-season. These include annuals, which flower in the same year in which they are raised from seed; and biennials, which only flower in the year following that in which they are sown. Examples are rice, wheat, banana, etc.

Caulocarpic: If, after flowering, the whole or part of the plant lives and produces fresh flowers in another season. These include herbaceous perennials, in which the greater part of the plant dies after flowering, leaving only a small perennial portion called the stock or caudex, close to or within the earth; undershrubs, suffruticose, or suffrutiscent plants, in which the flowering branches, forming a considerable portion of the plant, die down after flowering but leave a more or less prominent and woody base; shrubs (frutescent or fruticose plants), in which the perennial woody part forms the greater part of the plant, but branches near the base, and does not much exceed a man's height; and trees (arboreus or arborescent plants) when the height is greater and forms a woody trunk, scarcely branching from the base.

5.1.2.1 Terrestrial and Aquatic Plants

Based on the growing environment (soil or water), plants may be terrestrial and aquatic. Plants are usually *terrestrial*, that is growing on earth, or *aquatic*, i.e., growing in water; but sometimes they may be found attached by their roots to other plants, in which case they are *epiphytes* when simply growing upon other plants without penetrating into their tissue, *parasites* when their roots penetrate into and derive more or less nutrient from the plant to which they are attached.

5.1.2.2 C_3 and C_4 Plants

Based on the photosynthetic pathway, plants may be C_4 and C_3 types. The term C-4 refers to certain plants (such as sugarcane, that evolve in semi-arid tropical or sub-tropical areas) which have a special added metabolic pathway. Some of the intermediate compounds in this pathway are four-carbon acids, hence the term "C-4". These plants use some of their light energy to drive this extra path, but overall energy efficiency in air and bright sunlight is higher than other plants. The C-4 plants avoid a wasteful process called photorespiration that occurs in other plants at high light intensities. The C_4 pathway of photosynthesis is essentially a pumping mechanism that moves CO_2 from the mesophyll cells and cause high CO_2 concentrations in the biochemically active vascular-bundle sheath cells.

Atmospheric CO_2 concentrations are strongly inhibitive to CO_2 uptake in C_3 plants where CO_2 is fixed directly by RuBP carboxylase. For a given rate of transpiration, photosynthesis is greater in C_4 than in C_3 plants.

5.1.2.3 CAM Plants

The crassulacean-acid metabolism (CAM) has evolved in some desert succulents and cacti. CAM plants open their stomata primarily at night when they assimilate carbon dioxide into oxaloacetate. Daily water use is minimized but their growth is very slow.

5.2 Development of Plants

5.2.1 Growth Stages of Field Crops

There is a wise saying, "You can not manage what you do not observe and measure." A sound understanding of plant growth and development is an essential element of efficient and economic crop management systems. Growing conditions and management decisions at any stage can have a significant bearing on the ultimate performance of the crop. The impact of frost, heat, drought, diseases, insects, and weeds can be more accurately predicted with a clear picture of the relationships between growth stage and plant response to stress. The optimum timing (and need) of fertilizer, irrigation, herbicide, insecticide, and fungicide applications are also best determined by crop growth stage rather than calendar date. Also, crop monitoring to determine the timing of the occurrences of such yield-reducing factors as lodging, water-logging, and frost will, in combination with other severity, determine their effect on grain yield.

A number of staging systems have been evolved for describing the development of cereals. The ten major growth stages that the cereal plant progresses through during its life cycle are all familiar to us: (1) Germination, (2) Seedling, (3) Tillering, (4) Stem elongation or Jointing, (5) Booting, (6) Heading, (7) Flowering or Anthesis, (8) Milk, (9) Dough, (10) Ripening.

5.2.1.1 Numerical Measures of Growth and Development

Several systems have been developed to provide numerical designations for growth and developmental stages. Among these, the Feekes, Zadoks, and Haun scales are used the most frequently.

5.2.1.2 Feekes Scale

The Feekes scale was originally designed for wheat by Feekes (1941), and then illustrated and amended by Large (1954) (Table 5.1, Fig. 5.1). It recognizes 11

Table 5.1 Growth stages and corresponding Feekes scale (after Large 1954; with permission from Wiley-Blackwell)

Growth stage	Feekes scale	Crop growth description
Tillering	1	One shoot (number of leaves can be added)
	2	Beginning of tillering
	3	Tillers formed, leaves often twisted spirally. In some varieties of winter wheats, plants may be "creeping" or prostrate
	4	Beginning of the erection of the pseudo-stem, leaf sheaths beginning to lengthen
	5	Pseudo-stem (formed by sheaths of leaves) strongly erected
Stem elongation	6	First node of stem visible at base of shoot
	7	Second node of stem formed, next-to-last leaf just visible
	8	Last leaf visible, but still rolled up, ear beginning to swell
	9	Ligule of last leaf just visible
	10	Sheath of last leaf completely grown out, ear swollen but not yet visible
Heading	10.1	First ears just visible (awns just showing in barley, ear escaping through split of sheath in wheat or oats)
	10.2	Quarter of heading process completed
	10.3	Half of heading process completed
	10.4	Three-quarters of heading process completed
	10.5	All ears out of sheath
Flowering (wheat)	10.5.1	Beginning of flowering (wheat)
	10.5.2	Flowering complete to top of ear
	10.5.3	Flowering over at base of ear
	10.5.4	Flowering over, kernel watery ripe
Ripening	11.1	Milky ripe
	11.2	Mealy ripe, contents of kernel soft but dry
	11.3	Kernel hard (difficult to divide by thumb-nail)
	11.4	Ripe for cutting. Straw dead

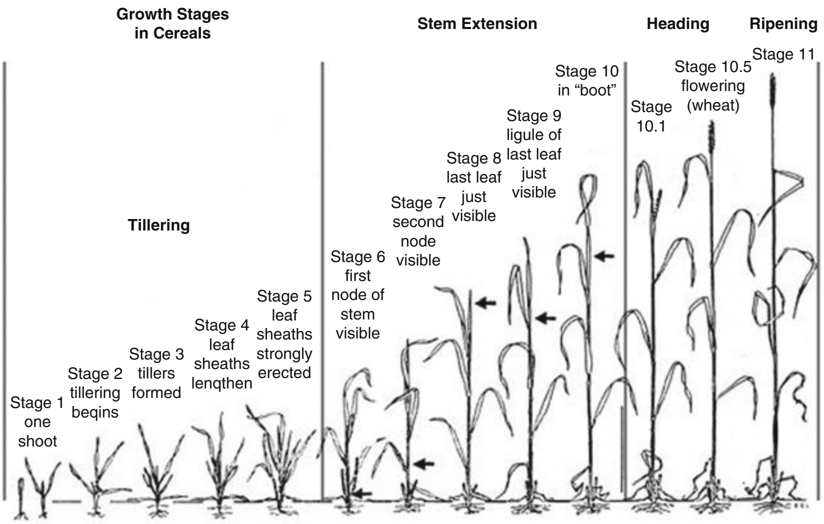


Fig. 5.1 Illustration of growth stages in cereal by Feekes scale (after Large 1954; with permission from Wiley-Blackwell)

major growth stages starting with seedling emergence and ending with grain ripening. The Feekes scale is frequently used to identify optimum stages for chemical treatments, such as fungicide applications, that focus on the plant development period from the start of stem elongation (Feekes stage 6) to the completion of flowering (Feekes stage 10.53). According to Large (1954), cereals develop as per Feekes growth stages (Table 5.1).

5.2.1.3 Zadoks Scale

The Zadoks decimal code (Z) is used internationally to describe growth stages of cereals. The Zadoks scale (Zadoks et al. 1974) covers all stages from seed to seed, using a two-digit, computer compatible, easy-to-memorize, numerical code (Table 5.2). It uses code based on ten major stages that can be subdivided, making it particularly suited for computerization.

The Zadoks's system applies to any small grain cereals (e.g., wheat, barley, rye, oats, and rice) and its stages are easy to identify in the field. It is more detailed than other systems and allows for precise staging. The first digit of this two-digit code (shown in Table 5.2) refers to the principal stage of development beginning with germination (stage 0) and ending with kernel ripening (stage 9). Use of the second digit between 0 and 9 subdivides each principal growth stage. A second digit value of 5 usually indicates the midpoint of the principal stage. For example, a 75 refers to medium milk stage of kernel development. In seedling growth, principal growth

Table 5.2 Description of the growth stages of the Zadoks decimal code for cereals (with consideration of wheat) (after Zadoks et al. 1974; with permission from Wiley-Blackwell)

Code	Stage	Code	Stage
	Germination		*Booting*
00	Dry seed	40	–
01	Water uptake (imbibition) started	41	Flag leaf sheath extending
03	Imbibition complete	45	Boot just swollen
05	Radicle emerged from seed	47	Flag leaf sheath opening
07	Coleoptile emerged from seed	49	First awans visible
09	Leaf just at coleoptile tip		*Heading*
	Seedling development	50	First spikelet of head visible
10	First leaf emerged	53	¼ of head emerged
11	First leaf unfolded	55	½ of head emerged
12	2 leaves unfolded	57	¾ of head emerged
13	3 leaves unfolded	59	Emergence of head complete
14	4 leaves unfolded		*Flowering/Anthesis*
15	5 leaves unfolded	60	Beginning of flowering
16	6 leaves unfolded	65	Flowering half complete
17	7 leaves unfolded	69	Flowering complete
18	8 leaves unfolded		*Milk*
19	9 or more leaves unfolded	70	–
	Tillering	71	Kernel watery
20	Main shoot only	73	Early milk
21	Main shoot and 1 tiller	75	Medium milk
22	Main shoot and 2 tillers	77	Late milk
23	Main shoot and 3 tillers		*Dough*
24	Main shoot and 4 tillers	80	–
25	Main shoot and 5 tillers	83	Early dough
26	Main shoot and 6 tillers	85	Soft dough
27	Main shoot and 7 tillers	87	Hard dough
28	Main shoot and 8 tillers		*Ripening*
29	Main shoot and 9 or more tillers	90	–
	Stem elongation or jointing	91	Kernel hard (difficult to separate by fingernail)
30	Pseudo stem erection	92	Kernel hard
31	1st node detectable	93	Kernel loosening in daytime
32	2nd node detectable	94	Overripe, straw dead, and collapsing
33	3rd node detectable	95	Seed dormant
34	4th node detectable	96	50% of viable seed germinates
35	5th node detectable	97	Seed not dormant
36	6th node detectable	98	Secondary dormancy
37	Flag leaf just visible	99	Secondary dormancy lost
39	Flag leaf ligule/collar just visible		

stage 1, the second digit refers to the number of emerged leaves. To be counted, a leaf must be at least 50 percent emerged. A 13, for example, indicates that three leaves are at least 50 percent emerged on the main shoot. Tiller leaves are not counted.

5.2.1.4 Haun Scale

The Haun scale growth stages are based on rate of development of the main shoot (Haun 1973). In the early stages, the description of each new leaf is related to the previous leaf that was produced. For example, a seedling with one fully extended leaf and a second leaf that is half as long as the fully extended leaf is at Haun stage 1.5. Similarly, a plant with five fully extended leaves on the main shoot and an emerging sixth main shoot leaf that is 30% as long as the fifth leaf is at Haun stage 5.3. The booting stage numerical designation starts at one more than the number of leaves produced by the main shoot, i.e., the flag leaf number plus one. This can cause confusion because the flag number is not a constant for all cultivars. For this reason, the Haun scale has been used mainly to describe the growth stages before the booting stage. Haun scale values from the booting to ripening stages are dependent on the number of leaves produced on the main stem.

5.2.1.5 Comparison Among Feekes, Zadoks, and Haun Scales

The scales differ in their scaling pattern and magnitude of the code. The differences among the Feekes, Zadoks, and Haun scale are illustrated in Table 5.3 with a sample crop, wheat.

5.2.2 Growth and Development of Cereals: Example with Wheat Plant

5.2.2.1 Growth Stages of Wheat

An understanding of crop growth and development is essential to achieve optimum productivity of the crop. The growth cycle of wheat has mainly the following divisions: germination, seedling establishment and leaf production, tillering and head differentiation, stem and head growth, head emergence and flowering, and grain filling and maturity. Bhuiya and Kamal (1991) identified 12 growth stages under six growth phases of different winter wheat cultivars in a sub-humid subtropic environment, having variations in duration in different varieties. The phases were germination and emergence (0–8 days), tillering (8–43 days), stem elongation (33–65 days), heading (55–75 days), flowering (61–81 days), and grain formation and ripening (65–115 days). The growth stages were emergence (0–8 days), seedling (9–18 days), crown root (17–29 days), tillering (22–43 days), jointing (33–51 days), shooting (42–59 days), booting (51–65 days), heading (56–75 days), flowering (61–81 days), milk (65–88 days), dough (79–98 days), and ripening (92–115 days).

Table 5.3 Comparative illustrations of wheat growth stages for Haun, Feekes, and Zadoks scales

Haun scale	Feekes scale	Zadoks scale	General description
0.0			*Germination*
		00	Dry seed
		01	Water uptake (imbibition) started
		03	Imbibition complete
		05	Radicle emerged from seed
		07	Coleoptile emerged from seed
		09	Leaf just at coleoptile tip
			Seedling development
		10	First leaf emerged
1.+	1	11	First leaf unfolded
1.+		12	2 leaves unfolded
2.+		13	3 leaves unfolded
3.+		14	4 leaves unfolded
4.+		15	5 leaves unfolded
5.+		16	6 leaves unfolded
6.+		17	7 leaves unfolded
7.+		18	8 leaves unfolded
8.+		19	9 or more leaves unfolded
			Tillering
		20	Main shoot only
	2	21	Main shoot and 1 tiller
		22	Main shoot and 2 tillers
		23	Main shoot and 3 tillers
		24	Main shoot and 4 tillers
		25	Main shoot and 5 tillers
		26	Main shoot and 6 tillers
		27	Main shoot and 7 tillers
		28	Main shoot and 8 tillers
		29	Main shoot and 9 or more tillers
			Stem elongation or jointing
	4–5	30	Pseudo stem erection
	6	31	1st node detectable
	7	32	2nd node detectable
		33	3rd node detectable
		34	4th node detectable
		35	5th node detectable
		36	6th node detectable
	8	37	Flag leaf just visible
	9	39	Flag leaf ligule/collar just visible
			Booting
		40	–
8–9		41	Flag leaf sheath extending
9.2		45	Boot just swollen
		47	Flag leaf sheath opening
10.1		49	First awans visible
			Heading
10.2	10.1	50	First spikelet of head visible
	10.2	53	¼ of head emerged
10.5	10.3	55	½ of head emerged
10.7	10.4	57	¾ of head emerged
11.0	10.5	59	Emergence of head complete

(*continued*)

Table 5.3 (continued)

Haun scale	Feekes scale	Zadoks scale	General description
			Flowering/Anthesis
11.4	10.51	60	Beginning of flowering
11.5		65	Flowering half complete
11.6		69	Flowering complete
			Milk
		70	–
12.1	10.54	71	Kernel watery
13.0		73	Early milk
	11.1	75	Medium milk
		77	Late milk
			Dough
		80	–
		83	Early dough
		85	Soft dough
		87	Hard dough
			Ripening
		90	–
	11.3	91	Kernel hard (difficult to separate by fingernail)
16.0	11.4	92	Kernel hard
		93	Kernel loosening in daytime
		94	Overripe, straw dead, and collapsing
		95	Seed dormant
		96	50% of viable seed germinates
		97	Seed not dormant
		98	Secondary dormancy
		99	Secondary dormancy lost

Some Relevant Terminologies

Before going through details about different growth stages and plant parts, it is useful to define some relevant terminologies used frequently.

Adventitious roots: Roots produced by crown nodes on the main shoot and tillers.

Crown: Several nodes whose internodes do not elongate.

Sheath: The tubular portion of a grass leaf that encloses the stem.

Spikelet: Subdivision of the head.

Radicle: The first root to emerge from the seed.

Seminal roots: The roots originating from the seed.

Photosynthate: The products of photosynthesis.

Coleoptile: The leaf sheath which surrounds and protects the embryonic plant as it emerges from the seed.

Leaf axil: The junction of the leaf with the main stem.

Internode: The region between two successive nodes.

Description of Growth Stages

Germination

When a seed is sown, the germination process begins. The radicle and seminal roots first extend, followed by the coleoptile (Fig. 5.2a). Roots can be initiated from several positions on the seedling, both at the level of the seed and at the crown (Fig. 5.2b, c). The crown is usually separated from the seed by a sub-crown internode. The length of this internode is greater as the depth of planting increases. As the coleoptile emerges from the soil, its growth stops and the first true leaf pushes through the tip.

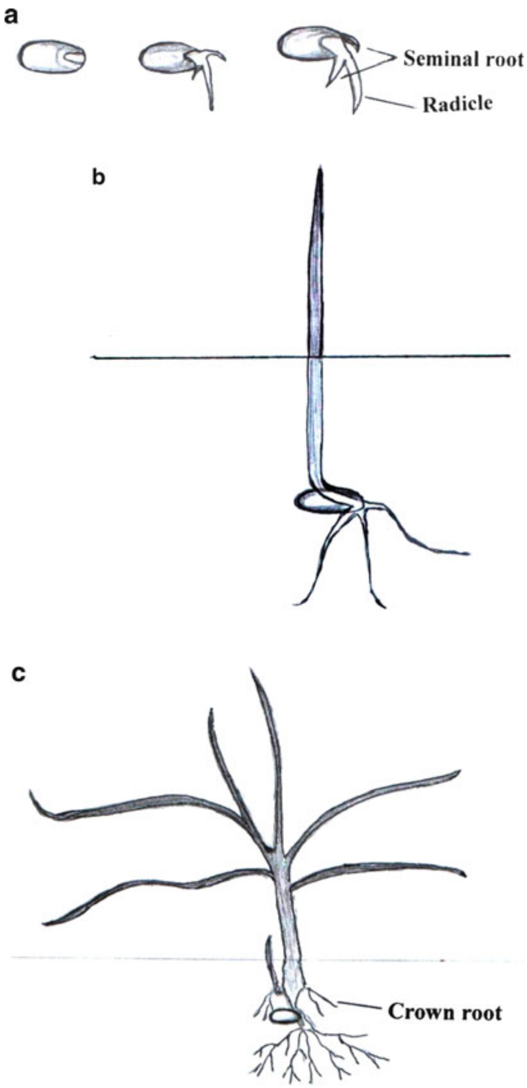


Fig. 5.2 (**a**) Schematic of wheat germination. (**b**) Sketch of wheat emergence. (**c**) Sketch of wheat plant with well developed crown

Seedling Stage

The seedling stage begins with the appearance of the first leaf and ends with the emergence of the first tiller. Up to six seminal roots and three leaves support the plant at this stage. The crown of the plant usually becomes noticeably distinct after the third leaf has emerged.

After seedling emergence, leaves are produced at a rate of about one every 4–5 days. A total of eight or nine leaves are usually produced: later maturing varieties have the larger number. Emergence of the last leaf (termed the flag leaf) is an important stage for timing the application of certain plant growth regulators.

Tillering and Head Differentiation

Tillering is an important development stage that allows plants to compensate for low plant populations or take advantage of good growing conditions. Tiller appearance is closely coordinated with the appearance of leaves on the main shoot. The number of tillers formed depends on the variety and growing conditions. Under usual field conditions, a plant may produce a total of three tillers in addition to the main shoot, although not all will necessarily produce grain. The capability also exists to produce tillers from tillers (termed secondary tillers) if the plant is not crowded or is heavily fertilized. Tillers that appear at the time that the fourth, fifth, and sixth leaves emerge on the main shoot are most likely to complete development and form grain. Tillers formed later are likely to abort without producing grain. Tillers that produce more than three leaves and initiate their own root system are most likely to survive. The proportion of initiated tillers that abort differs with the variety and can increase if the crop encounters stress conditions.

During the time that tillering occurs, another less obvious but extremely important event occurs: the initiation of heads on the main shoot and tillers. Although the head at this time is microscopic, the parts that will become the floral structures and kernels are already being formed. When head formation is complete, the stem begins elongating. This corresponds to the “jointing” stage. A plant usually has about five leaves at this time.

Stem and Head Growth

Lower stem internodes on the plant remain short throughout development. The fourth internode is usually the first to elongate in a plant with nine total leaves. This is followed in sequence by the internodes above it. Each stem internode up the plant becomes progressively longer, and the last stem segment to elongate, the peduncle, accounts for a considerable proportion of the total stem length. Growth regulators that are designed to shorten plant stature and increase resistance to lodging are timed to influence stem elongation. Some regulators act as growth retardants and reduce elongation of the last two or three stem internodes, resulting in a shorter, stiffer stemmed plant that lodges less readily.

Stem elongation coincides with the period of rapid head growth in which the individual florets become prepared to pollinate and be fertilized. Throughout the pre-heading period, differences in the duration of the various developmental phases among shoots on the same plant help synchronize development. This means a difference of several weeks between emergence of the main shoot and a tiller is reduced to a difference of only a few days by the time the heads emerge from the flag leaf sheaths. The "boot" stage is just prior to head emergence, when the flag leaf sheath encloses the growing head.

Head Emergence and Flowering

As the stem continues to elongate, the head is pushed out of the flag leaf sheath, a stage referred to as "heading." Within a few days after heading, flowering (pollination) begins in the head, starting first with the florets in the central spikelets. Within the next few days flowering progresses both up and down the spike.

Flowering is usually noted by extrusion of the anthers from each floret, although this can change depending on the variety and weather conditions. If the anthers within a floret are yellow or gray rather than green, it is reasonably certain that pollination of the floret has occurred. The period of pollination within a single head is about 4 days. The young kernels within a head vary considerably in size at pollination and maintain this size variation throughout grain filling to maturity. The flowering or anthesis stage lasts from the beginning to the end of the flowering period. Pollination and fertilization occur during this period. All heads of a properly synchronized wheat plant flower within a few days, and the embryo and endosperm begin to form immediately after fertilization.

Milk Stage

Early kernel formation occurs during the milk stage. The developing endosperm starts as a milky fluid whose solid content increases as the milk stage progresses. Kernel size increases rapidly during this stage.

Dough Development Stage

Kernel formation is completed during the dough development stage. The kernel accumulates most of its dry weight during dough development. The transport of nutrients from the leaves, stems, and spike to the developing seed is completed by the end of the hard dough stage. The developing kernel is physiologically mature at the hard dough stage even though it still contains approximately 30% water.

Ripening Stage

The seed loses moisture, and any dormancy it may have had, during the ripening stage.

Adverse environmental conditions during any of the growth periods of a kernel can reduce the rate of dry matter accumulation and decrease yield. As a rule, the longer the adverse condition lasts, and the earlier it occurs during grain filling, the greater its effect on yield. Throughout grain filling the kernel moisture percentage declines, finally reaching a level between 30 and 40% at the time of maximum grain weight (physiological maturity). However, kernel moisture does not always determine when physiological maturity occurs. A better indicator of maturity is when the head and the peduncle lose their green color. The green color is lost from the flag leaf blade when the kernel has attained about 95% of its final dry weight. Once the crop is at physiological maturity, no more kernel dry weight will accumulate and it can be harvested without reducing yield. After physiological maturity, moisture in the kernels declines rapidly.

5.2.2.2 Critical Growth Stages of Wheat

An understanding of how plants respond to environmental stresses at different growth stages can assist in the assessment of crop condition and production potential throughout the growing season. Winter wheat plants must survive against many stresses of winter. Roots and leaves that develop in the fall are often killed off during the very cold period. However, as long as the crown remains alive, new roots and leaves can be regenerated. Therefore, plants that enter the winter with well-developed crowns have the best chance of winter survival.

The number of viable seeds planted and the number of tillers produced per plant sets the upper limit on the number of heads that can be produced by a wheat crop. Crown root initiation stage plays a significant role in plant vigor and tiller initiation. Tiller production is favored by moist, warm weather and good soil fertility, especially nitrogen fertility, prior to the stem elongation stage.

Tillers produced during the tillering stage must survive to maturity to contribute to grain yield. The developing head and elongating stem start making large demands on the plants' resources once stem elongation starts and younger, poorly developed tillers that are unable to compete are quickly lost. Drought and heat stress during the stem elongation and booting stages increase the rate of tiller mortality by placing added restrictions on resource availability. If a drought is broken or a late application of nitrogen fertilizer suddenly becomes available during this period, the developmental synchrony of the plant may be disrupted producing a flush of later maturing heads.

Environmental stress prior to flag leaf appearance can result in a loss of spikelets on the developing head. As many as 12 florets per spikelet can be initiated under favorable conditions for development. However, later forming florets abort, and normally only two to four florets actually set seed in each spikelet. Floret initiation starts in the lower central region and progresses toward the base and tip of the head. Under extreme environmental stress, all of the florets in the spikelets at the top and bottom of the head may abort prior to flowering.

5.2.2.3 Grain Yield Production

Sources of Photosynthates for Grain Yield

Approximately 70–90% of the final grain yield is derived from photosynthates (products of photosynthesis) produced by the plant during grain filling (the remaining from pre-stored carbohydrates in vegetative parts). The flag leaf and head usually contribute most, but certainly not all, of the photosynthate to the grain. Photosynthates produced by the flag leaf may contribute up to 50% of the grain yield, depending on seasonal conditions, but the head, penultimate leaf, and other leaves can also contribute significant quantities. Maintaining green and functional upper leaf blades, sheaths, and heads during grain filling is important for high yields.

Cool temperature with sunny days favor wheat growth and yield, as cool temperature requires less respirational energy loss and bright sunshine increase photosynthesis (more energy gain).

Expression of Wheat Yield

Grain yield of wheat can be expressed as the product of yield components as (Ali et al. 2007):

$$\begin{aligned}\text{Grain yield}/\text{m}^2 = {} & (\text{number of effective tiller or panicle}/\text{m}^2) \\ & \times (\text{seed}/\text{panicle}) \times (\text{average unit seed weight}) \end{aligned} \tag{5.1}$$

The impact of each yield component on final grain yield is determined at different stages during the growing period.

5.2.3 *Thermal Time Requirement of Crop*

Crop growth and development is often described in terms of days from sowing, e.g., 50-day wheat, frost-free days, heading date, etc. However, a consideration of temperature is also important because temperature determines the rate of growth and development. The time–temperature unit that governs plant growth and development is known as thermal time and it is measured in heat units or growing-degree days. Heat unit is often used to avoid confusion between growing-degree days and calendar days.

The thermal time required for crop production is determined by adding the daily heat units together for the period between planting and harvest. Details about the importance of heat unit and calculation procedure of different heat units have been described in Chap. 2 (Climate). The thermal time provides an explanation for differences in crop maturity when observations from different years are compared.

5.3 Structure of Plant

5.3.1 General Structural Overview

A crop plant has two main organ systems: (1) the shoot system and (2) the root system. The shoot system is above ground and includes the organs such as leaves, buds, stems, flowers (if the plant has any), and fruits (if the plant has any). The root system includes parts of the plant below ground, such as the roots, tubers, and rhizomes.

Functions of Shoot System

- Elevates the plant above the soil
- Many other functions including the following:
  - Photosynthesis
  - Reproduction and dispersal
  - Food and water conduction

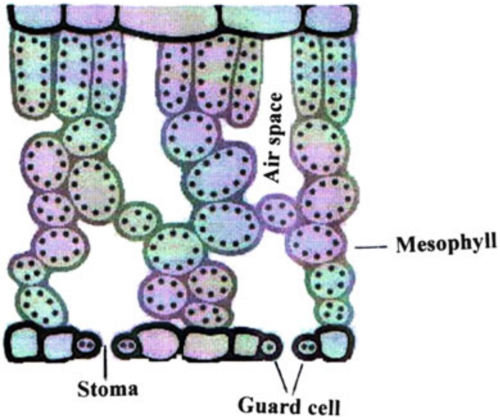
Functions of Leaf

- Trap light energy for photosynthesis
- Produce sugar by photosynthesis
- Exchange of gases – oxygen and carbon dioxide

Leaves are designed to allow carbon dioxide to get to the main chlorophyll layer at the top of the leaf. They have small holes called stomata on the under surface. Each hole is open and closed by two guard cells (Fig. 5.3).

Stomata open and close at different times of the day. When it is light, the plant needs CO_2 for photosynthesis so the stoma open; and at night (darkness) they close. The closure of stomata is also influenced by water content of the guard cells. As the turgor pressure of the guard cells increase, the cells swell outward and open the stomatal pore. On the contrary, when the turgor pressure of the cells decrease, the cells shrinks inward and then the stomatal pore closed. High temperature may also close stomatal closure. This may probably results from enhanced respiration and increased levels of CO_2 in the stomatal cavities. Stomatal behaviour may be different in different plant species, leaf position on the plant, stage of growth, and environmental conditions.

Fig. 5.3 Sketch of leaf structure – stoma and guard cell



Roots

The roots of crop plants are underground parts that spread widely through the soil and absorb water and mineral matter which they conduct to the stems and leaves. Roots ordinarily produce neither buds, leaves, nor flowers. Their branches, called *fibers* when slender and long, proceed irregularly from any part of their surface.

Roots may be as follows:

Fibrous: when they consist chiefly of slender fibers.

Tuberous: when either the main root or its branches are thickened into one of more short fleshy or woody masses called *tubers*.

Taproots: when the main root descends perpendicularly into the earth, emitting only very small fibrous branches.

Functions of Root

- Anchor the plant in the soil
- Absorb water and minerals from the soil
- Conduct water and nutrients
- Store food reserves

5.3.2 Root Growth and Development

5.3.2.1 Root Growth

When a seed germinates, the *primary root* develops at the lower end of the tiny stem of the embryo plant. Very soon, lateral roots begin to appear which, with their branches, greatly increase the absorbing area and anchoring power of the root. Many cereals, such as wheat, oats, and corn, usually have three roots arising from the seed (seminal roots), i.e. the primary root and two almost equally large laterals. These with their branches (sometimes supplemented by other primary roots) constitute the primary root system. In the case of the cereals and other grasses which have strong, threadlike or *fibrous roots* the larger part of the root system is composed of the adventitious roots which collectively make up the *secondary root system.*

Plant roots are responsible for nutrient and water uptake and provide physical support to the plant. Most of the root system is made of lateral roots that originate postembryonically. Lateral root development is controlled by different factors including nutrient concentration in the plant and the soil. This plasticity allows adaptation of the root system to the soil, a very heterogeneous and changing environment, and is consequently very important for the survival of the plant.

5.3.2.2 Structure of Root

Internally, the roots of all cultivated plants are built on the same general plan and differ from one another only in detail. Although the growing root ends are usually only about a millimeter in diameter, they show a wonderful differentiation and are remarkably adapted to perform their several functions (Fig. 5.4).

The amount of water and air in the soil has a marked effect upon the development of root hairs. The roots of cultivated crops usually produce few root hairs in wet soil. In moderately moist soil corn roots are almost woolly with root hairs, but there are fewer in wet soil, and usually none in water. The same general relation's hold for most cultivated plants, although there are some exceptions. Wet soils contain less air than dry ones and a good oxygen supply seems necessary to promote

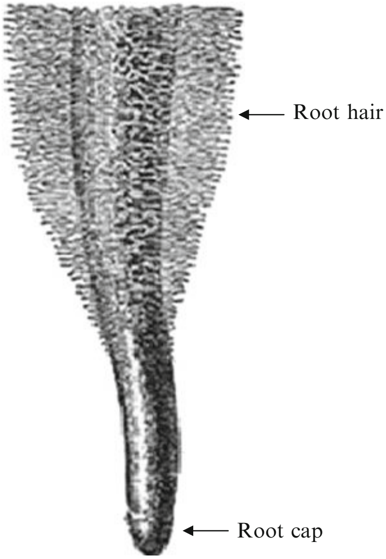


Fig. 5.4 Schematic view of root structure (showing root cap, root hairs)

abundant development of root hairs, at least in many species. Most cultivated plants require a well-aerated soil. Indeed, one of the chief advantages of stirring the soil is to admit air to the roots. In cultivated plants, so long as they do not wilt, it has been observed that the most abundant production of root hairs takes place at a water content somewhat less than that which will afford the highest yield. Of course, if soils become very dry, both root hairs and young rootlets die. Root-hair development may also be retarded by a very concentrated soil solution such as that occurs in alkali soils. Extremes of temperature are also inimical to their growth. They develop in the light and dark about equally well, provided there is ample moisture. The great importance of roots hairs may be realized when it is found that absorption is practically limited to the root-hair zone.

5.3.2.3 Relation of Roots to Soil Moisture

Crops respond to differences in water content and aeration, both in amount and direction of growth. By varying these factors by the application of more or less water, not only the root system but also the aboveground plant parts and yields may be varied, since a close correlation exists between the growth of roots and tops. The necessary water can be applied more effectively if a knowledge of the extent and position of the root system as modified by the chemical and physical nature of the soil is known.

If the subsoil is water-logged and thus unaerated, deeper roots will not develop or, if already grown, will soon die as the water table rises. In either case, there is a marked tendency toward the production of an abundance of roots so superficially placed that cultivation results in more or less serious root pruning. Moreover, under such conditions, plants are more sensitive to drought, temperature changes, etc. They require heavier irrigation and greater amounts of fertilizers than those more deeply rooted.

5.3.2.4 Factors Affecting Root Development and Adaptation

Some crops are better adapted to semiarid regions than others. The reason may sometimes be explained, at least in part, by a study of the root habit. Root distribution and development is greatly modified by various cultural practices. For example, loosening the soil by plowing results in increased storage of water and better aeration. This not only makes conditions more favorable for seed germination but affords better conditions for the growth of roots and for soil organisms such as nitrate bacteria. The latter produce greater amounts of nitrates which, in turn, affect root growth. Fertilizing the surface layers of soil, especially with nitrates, and thus stimulating surface root production in regions where these layers have very little or no available water during periods of drought appears to be distinctly detrimental to normal crop production. The effect of phosphates in promoting root growth in length and number of branches has long been recognized in agricultural practice.

Layers of compact soil often play an important part in shaping the root system. Depth of water table also influences the length of root. Depth of plowing, listing, or sub-soiling and the preparation of the seed bed, as well as the time, depth, and manner of subsequent cultivation influence the rooting system. Moreover, the loosened soil makes root penetration easier. Roots tend to develop a shorter and more compact structure in dense than in loose soils. Subsoiling carries the air still deeper and at the same time raises more minerals to the surface soil layers. It modifies in many ways the physical, chemical, and biological factors of the soil. All these changes are ultimately reflected in root habit.

5.3.2.5 Transport of Assimilates

It has been mentioned that a system of vascular bundles runs through all higher plants. It evolved as a response to the increase in the size of plants, which caused a progressing separation of roots and leaves in space. Thus, plants developed systems for long distance transport – i.e., translocation. The system consists of xylem and phloem. The xylem is the tissue that translocates water and minerals. Transport occurs acripetally, i.e., in the direction of the shoot's tip. The phloem is the tissue that translocates assimilates from mature leaves to growing or storage organs and roots. It serves, too, to redistribute water and various other substances. It may run either basipetally, i.e., in the direction of the root or bi-directionally (both acripetally and basipetally).

Xylem Transport

The xylem of a living plant is an interconnected, water-containing apoplastic system of communicating tubes in which the water holds together by cohesion forces. The xylem transports water and dissolved ions. The main portion of the water is taken up by young roots. Absorption occurs directly by the rhizodermis, and the area that takes up water and ions is enlarged by the formation of root hairs. From there flows the water through the cortex that may be developed as an exodermis, through the endodermis, the innermost layer of cortical cells and into the cells of the stele's vascular bundles. It is then transported through the roots to the shoot and finally into the leaves where it is given off by transpiration.

5.4 Crop Growth Factors

Plant growth and development is dependent on abiotic (physical) and biotic (biological) factors. Abiotic factors include the physical environmental conditions and biotic factors include animals, insects, and diseases.

Among abiotic factors, crop growth is influenced by the following:

- Climatic factor
- Water
- Nutrient

Crop growth is also influenced by growth hormone, if it is artificially applied. In addition, cultural practices that enhance the development of healthy, vigorous root systems result in efficient uptake and use of available nutrients. This category includes managing and maintaining crop residue, composting, liming to maintaining soil pH, reduced tillage, manuring, establishing diverse crop rotations, growing crop covers, etc.

5.4.1 Climatic Factors

Each crop has certain environmental requirements. To attain the highest yield (potential yield), a crop must be grown in an environment that meets these requirements. The main climatic elements determinant to crop growth and yield include temperature, solar radiation, and CO_2 concentration.

5.4.1.1 Temperature

Each crop grows and develops well at a favorable range of air temperature. This range is termed as optimum air temperature range. The temperature determines the speed of respiration and the dark reaction. A high temperature combined with a low intensity of sunlight means a high loss by respiration. A low temperature combined with a high intensity of sunlight means high net assimilation.

5.4.1.2 Solar Radiation

Solar radiation (also called photosynthetic active radiation (PAR)) is the energy source for green plant growth. The PAR powers the light reaction, which converts carbon dioxide and water into glucose and molecular oxygen. When temperature, moisture, carbon dioxide and nutrient levels are optimal, light intensity determines maximum production level. The potential drymatter production for a specific location under the prevailing light or solar radiation can be determined from the mathematical formula, as described in Chap. 3 (Weather).

5.4.1.3 Carbon dioxide Levels

Atmospheric carbon dioxide is the sole carbon source for plants. About half of all proteins in green leaves have the sole purpose of capturing carbon dioxide. Although CO_2 levels are constant under natural circumstances, CO_2 fertilization is common in greenhouses and is known to increase yields by an average 24%. The C_4 plants like maize and sorghum can achieve a higher yield at high solar radiation intensities, because they prevent the leaking of captured carbon dioxide due to the spatial separation of carbon dioxide capture and carbon dioxide use in the dark reaction. This means that their photorespiration is almost zero. This advantage is often offset by a higher maintenance respiration level.

5.4.2 Water and Nutrient Supply

5.4.2.1 Water Supply

Optimum soil-water supply (i.e., good irrigation practices) are critical to maintain a good crop growth and facilitating effective uptake of nutrients. As the plants use passive transport to transfer water and nutrients from their roots to the leaves, water supply is essential to growth.

5.4.2.2 Nutrient Supply

For optimum growth and high-quality harvested products, supply of adequate plant nutrients is essential. Nutrient supply has a twofold effect on plant growth. A limitation in nutrient supply will limit biomass production. In some crops, several nutrients influence the distribution of plant products in the plants. A nitrogen gift is known to stimulate leaf growth and therefore can work adversely on the yield of crops which are accumulating photosynthesis products in storage organs, such as ripening cereals or fruit-bearing fruit trees.

5.5 Crop Growth Parameters

5.5.1 Leaf Area Index

Leaf area index (LAI) is defined as the ratio of leaf area to land area under the leaf, i.e.,

$$\mathrm{LAI} = \frac{\text{leaf area}}{\text{land area under the leaf}}$$

LAI is a function of growth stage (or time of the life cycle) and type of the crop. It is also influenced by the available heat energy and management factors. For field crops, the LAI reaches its maximum value at the end of vegetative stage (or about 50% of its life span). The general trend is mostly like the graph given below (Fig. 5.5):

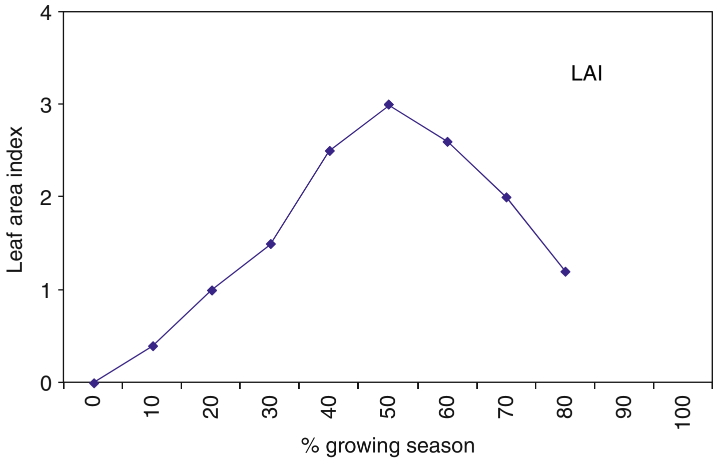


Fig. 5.5 Leaf area index (LAI) as a function of percent growth period

Green leaf area is the effective leaf area which contributes in photosynthesis process through interception of solar radiation. For the same type of crop, the LAI may vary depending on the varietal (i.e. genetical) difference.

The more the LAI, the more the carbohydrate assimilation.

5.5.1.1 Determination of LAI

Leaf area index is determined from the destructive plant samples. Leaves are separated from the stems and the leaves are weighed. Samples of the leaves are run through a leaf area machine (e.g., Portable Area Meter, Model L1-3000) to determine the area of leaves. Then, leaf area index is computed using the above formula.

Instead of determining the leaf area of the whole sample, sub-samples of the leaves can be used. In such case, the sub-sample is weighed and the sub-sample is run through a leaf area machine to determine the area of leaves. The leaf area of the whole sample is determined based on the leaf area per unit fresh weight of the sub-sample and the leaf biomass per unit sample area. That is,

$$\begin{aligned}\text{Leaf area of the whole sample} = {} & (\text{leaf area of the sub-sample}/\\ & \text{fresh weight of the sub-sample})\\ & \times \text{fresh weight of whole sample}\end{aligned}$$

Then, leaf area index is computed.

It is not wise to take the dry (oven-dry, at about 70–80°C) weight of leaf subsample to determine the leaf area of the whole sample because the dry weight of the leaf is very low, and there are possibilities of making errors while taking the dry weight and maintaining uniformity of dryness.

Specific leaf area (SLA)

It is the leaf area per unit of dry mass. That is,

$$\mathrm{SLA} = A/M$$

Where

A = area of leaf

M = mass of the leaf

5.5.2 Growth Rate and Relative Growth Rate

Growth is the process by which a plant increases in the number and size of leaves and stems. It can be said as an irreversible change in the size of a cell, organ, or whole organism. The Growth rate (GR) refers to development per unit time, i.e.,

$$\mathrm{GR} = \frac{L}{T} \quad (\mu \text{ per second}).$$

Under given normal conditions, different plants show different rate of growth. This is due to their genetic potentialities. Growth rate also varies with factors in the environment.

Relative Growth Rate

Relative growth rate (RGR) is computed from two sampling event as follows:

$$\mathrm{RGR} = (\log_e W_2 - \log_e W_1)/(t_2 - t_1), \tag{5.2}$$

where

W_2 is thefresh weight of plant sample of particular (or unit) area at time t_2,

W_1 is the fresh weight of plant sample of the same area at time t_1, and $t_2 - t_1$ is the time interval in days between those harvests.

The RGR represents that growth obtained relative to the amount of tissue at present, expressed as a daily average. This is a reflection of growth potential under the conditions imposed. The RGR may also be expressed as a dry-weight basis.

In that case, the harvested plants are to be dried at 70°C until constant weight is achieved.

5.5.3 *Root Study*

Shoot and root development are closely linked and coordinated as growth proceeds. If the environment is constant, a logarithmically linear relationship usually exists between the weight of shoots and roots during vegetative growth. Modeling of water and nutrient uptake during crop growth requires quantitative information on root development. Besides, to quantify the effect of fertilizer and/or irrigation on growth and yield, root information is needed because; root is the organ of the plant which takes up necessary nutrient and water for the plant.

5.5.3.1 Root Length Density

Root length density (RLD) is defined as the root length per unit soil volume, i.e., the ratio of total root length under a certain volume of soil to the volume of soil under consideration:

$$\mathrm{RLD} = \frac{\text{total root length}}{\text{total volume of soil}} \tag{5.3}$$

RLD is generally expressed in $\mathrm{cm/cm^3}$ of soil.

5.5.3.2 Method of Root Sampling

Various methods are available for root sampling and measurement. Root sampling methods include auger hole method, pit sampling method, etc.

Auger Hole Method

The auger hole method is simple compared to other methods to determine root distribution and root density. Auger size may range from 5 to 10 cm (inner diameter). But sampling with 10 cm provides a good estimate for shallow-rooted crop like wheat (Kumar et al. 1993). The position of sampling should be between on the row and midway between rows. A large number of samples are required to obtain a reasonable accurate estimate of average root density.

Root sampling is carried out at different time of growth period (e.g., 45, 60, and 85 days after sowing (DAS)).

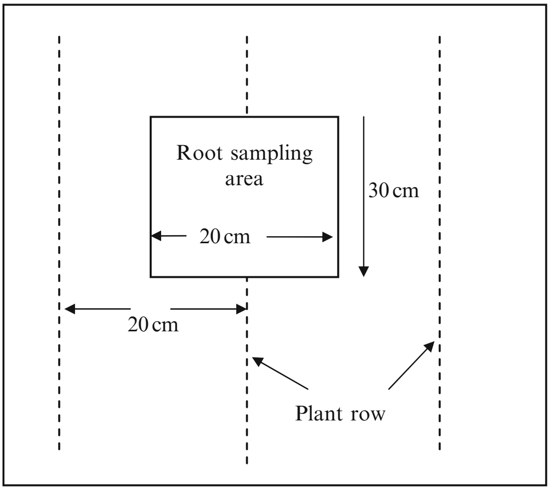


Fig. 5.6 Schematic view of the root sampling area

Pit Sampling/Soil Monolith Sampling

Pits are dug covering row and half-way between rows in both sides of a row (as shown in Fig. 5.6). Pits can be dug easily with small shabowls and locally available tools. An ideal pit size depends on the plant type and the depth of sampling depends on plant type and period of growing season. For wheat, with 20 cm line spacing, an ideal size of pit may be at 30 cm × 20 cm × 15 cm, where 30 cm is along row, 20 cm is normal to row, and 15 cm deep. Separate sample for each 15-cm incremental depth may be collected to observe the distribution pattern as and when necessary (depending on the development stage of the crop).

Processing of the Sample and Preparing the Roots for Measurement

The soil from each core or pit section may be cleaned by placing on a 32-mesh screen and washing in a water channel providing gentle pulse by wrist action. The roots can also be cleaned by first diluting the soil sample (containing root) in a large bucket and then passing the solution through a mesh (or any other locally available fine net or net-like cloth bag). The main problem of washing roots through sieves is that the fine root segments are lost through the sieve. The most appropriate sieve size depends on the plant species and soil texture. Ideally, the size should be such that it allows the soil particles to pass through easily and retain the roots, or there should be some compromise within the permissible limit. Kumar et al. (1993) reported that washing wheat roots in cloth bags yielded significantly more roots than washing in sieves of 16 or 32 meshes. After passing through mesh or net, the roots are separated from the underground step, stones, grass roots, and rhizome parts. The living roots are kept frozen till their lengths are measured.

5.5.3.3 Measurement of Roots

Length Measurement

Lengths of root can be measured following different techniques given below:

By millimeter paper: In this method, the washed roots are positioned in series in a millimeter paper in which the scales are written from zero point. The lengths are summed to obtain the total length.

Line intercept technique: The length of the roots can also be measured by the line-intercept technique of Newman (1966).

Taking Weight of Roots

To express the root density in weight basis, the roots are dried in an oven at 70°C for 48 h and weighed. It is expressed as gm/cm^3 (gm root per cubic centimeter of soil).

Root to Shoot Weight Ratio

Ratio of root to shoot dry weight is computed as the ratio of root weight to the total weight of leaves and stems. The ratio can be determined on fresh weight basis or dry weight basis, as required.

5.5.3.4 Increasing Available Water Supply for Plant Root

Crop drymatter yield increases approximately linearly with total evapotranspiration and nutrient availability. This suggests that increasing the quantity of water available for transpiration will increase yield if water supply is limiting yield. Increasing the abstracting area by expansion of root will also increase opportunity to take up nutrients.

One method of increasing the supply of available water is through increasing the total soil volume occupied by the plant's root. This can be achieved by either a greater lateral spread or a greater rooting depth. Optimum tillage and deep tillage can facilitate for such type of expansion. The *second method* for increasing available water supply is through increasing root length density in soil zone from where water is lost by evaporation or deep percolation. Root length density may increase as a result of increased initiation of secondary roots and increased elongation rate of secondary roots. *Third method* for increasing total available water is through increasing the root water uptake rate in soil zone where water is lost rapidly. Soil management techniques that increase soil water content (such as addition of organic matter, mulching) may increase water uptake. The *Fourth method* for increasing total available water is through reducing axial resistance to water flow in the root xylem. This reduction in resistance permits more water to flow for photosynthesis.

5.6 Dry-Matter Production in Plant and Its Partitioning

Usually only a fraction of the total plant biomass consists of useful products, e.g., the seeds in pulses and cereals, the tubers in potato and cassava, the leaves in sisal and spinach, etc. The yield of usable plant portions will increase when the plant allocates more assimilates to these parts. For example, the high-yielding varieties of wheat and rice allocate about 40–50% of their biomass into wheat and rice grains, while the traditional varieties achieve only 20–30%, thus doubling the effective yield.

De Wit (1958) originally pointed out that drymatter accumulation of a plant is related to transpiration. This was the basis of simple and relatively complex models of drymatter production by crops and pastures in water-limiting condition. Portioning of drymatter into different parts of the plant (shoot, root, fruit or grain) depends on the percentage growing period, limitations of other essential resources (water or nutrient), and any other adverse condition or stress (e.g., salinity stress, heat, or cold stress).

5.6.1 Determination of Total Biomass or Drymatter

Total above-ground drymatter can be determined by harvesting the stover at the ground surface and taking fresh weight. By drying 1 kg sample (of each category or treatment) at 85°C for constant weight (~48 h), the total fresh weight can be converted to dry weight.

For total biomass, root weight should also be included.

5.6.2 Indices of Drymatter Partitioning

5.6.2.1 Root–Shoot ratio

It is the ratio of root weight to the weight of total above-ground matter or shoot. That is,

$$\begin{aligned}\text{Root} - \text{Shoot ratio} &= \text{wt. of root/wt. of shoot}\\ &= \text{grain yield/total aboveground biomass}\end{aligned}$$

The weight can be of fresh weight or dry weight. The ratio indicates the percent distribution of total biomass into root and shoot.

5.6.2.2 Harvest Index

Harvest index (HI) is defined as the ratio of grain or seed yield to the sum of grain and straw yield, i.e.,

$$\mathrm{HI} = \text{grain yield}/(\text{grain yield} + \text{straw yield}).$$

Harvest index indicates the proportion of grain yield to total aboveground drymatter. That is, it actually indicates the percentage of aboveground drymatter accumulated to grain. Its value for field crops normally ranges between 0.25 and 0.36, depending upon the crop and species.

5.6.2.3 Harvest Ratio

The harvest ratio (HR) is defined as the ratio of grain or seed yield to the straw yield, i.e.,

$$\mathrm{HR} = \frac{\text{grain yield}}{\text{straw yield}}.$$

Harvest ratio indicates the proportion of grain weight to straw weight. Usually, its value ranges from 0.45 to 0.55 for the high-yielding modern crop varieties. The higher value of *HR* indicates the higher proportional accumulation of assimilates to grain, which indirectly indicates higher efficiency for resource utilization. Although harvest index and harvest ratio represent similar meaning, but the harvest ratio gives a clear picture of assimilate partitioning. Harvest ratio can be used as an indicator for selecting cultivar in breeding program as well as in resource-limiting condition. Cultivars having higher *HR* accompanied by higher or comparable yield, may be selected for commercial production. In determining *HI* and *HR*, the grain and straw yield must be adjusted to a certain (fixed) percentage of moisture content (normally at 12% moisture for cereals). It can be done using the following equation (Ali 2008):

$$Y_{\mathrm{adj}} = Y_{\mathrm{i}} \times \frac{(100 + M_{\mathrm{t}})}{(100 + M_{\mathrm{i}})} \tag{5.4}$$

where M_{i} is the initial moisture content, Y_{i} is the initial yield (at M_{i} moisture content), M_{t} is the targeted moisture content (say, 12%), and Y_{adj} is the adjusted yield (at M_{t}% moisture content).

5.6.3 Assimilate Partitioning/Remobilization of Prestored Carbon

Grain filling is the final stage of growth in cereals where fertilized ovaries develop into caryopses. At this stage, about 40–50% of total biomass is deposited into the grains. Delayed whole plant senescence, leading to poorly filled grains and unused carbohydrate in straws, is a new problem increasingly recognized in rice and wheat production (Zhang et al. 1998). Slow grain filling may often be associated with delayed whole plant senescence. Monocarpic plants such as rice and wheat need the initiation of whole plant senescence so that stored carbohydrates in stems and leaf sheaths can be remobilized and transferred to developing grains (Zhang and Yang 2004). Normally when these crops are grown in high-input system, pre-stored carbohydrates contributes one-fourth to one-third to the final weight of grain.

5.6.4 Improving Assimilate Partitioning to Grain

In most crops (especially in cereals), we are interested to produce higher grain yield, but not the straw yield. Harvest index has been shown as a variable factor in crop production, especially in cases where whole plant senescence of cereals (e.g., rice and wheat) is unfavorably delayed. Such delayed senescence can delay the remobilization of pre-stored carbon reserves in the straw and results in lower harvest index. Controlled soil drying can enhance whole plant senescence and, therefore, improves the remobilization of pre-stored carbon reserve. Gains from the improved harvest index may outweigh any possible biomass loss due to shortened photosynthetic period in grain filling. Yang et al. (2001) noted that the early senescence induced by water deficit does not necessarily reduce grain yield even when plants are grown under normal nitrogen conditions. Zhang et al. (1998) found with field-grown wheat that a soil drying during the grain-filling period enhance early senescence. They found that while the grain filling was shortened by 10 days (from 41 to 31 days) in unwatered (during this period) plots, a faster rate of grain filling and enhanced mobilization of stored carbohydrate minimized the effect on yield. Zhang and Yang (2004) showed that water productivity (WP) may be enhanced through an improved harvest index (HI). Ali (2008) found highest harvest index, harvest ratio and irrigation water productivity with drying at grain filling stage.

5.7 Plant Water Relations

5.7.1 Theoretical Perspectives

Water is considered by most plant biologists and forest scientists to be the single most important environmental factor influencing plant growth and distribution. Water plays an important role in plants. It maintains the turgor pressure in the cells, and it cools the leaves as it evaporates. Water is the largest component of plants. Actively growing tissue (leaves, root tips) can be 80–90% water. Woody parts of trees are a much lower percent of water ranging between 45 and 60% water by weight. Water serves as the solvent which transports minerals and dissolved carbohydrates throughout the plant. Because of its unique chemical properties, water is an excellent overall solvent and is therefore able to dissolve many chemical substances. Water is also a reactant in many chemical reactions in the plant. Probably the most significant of these is photosynthesis, where water serves as the source of electrons. The oxygen we breathe every day is a result of this reaction in photosynthesis. Another important function of water is that it maintains turgidity (or pressure) in plant tissue. This "turgor pressure" is necessary for cell enlargement, growth and even maintenance of form in some plants. One of the first visible signs of a lack of water is wilted (or "deflated") leaves.

Water movement from cell to cell in plants occurs along gradients of water potential. Water potential is actually a measure of the "free energy" of water. Water moves from regions of high to low free energy or from regions of high to low water potential. For the sake of convenience, plant biologists have defined pure water as having a water potential of zero.

Water relations data of plants in different environments facilitates understanding about how plants "adjust or adapt" in order to maintain an appropriate water status that is necessary for survival and growth. Physiological interpretation of water relations data provides insight about the mechanistic processes that allow plants to maintain appropriate water status. Specifically, water and osmotic potentials, turgor, relative water content, and transpiration of plants without or under varying water stress conditions are to be determined and interpreted.

Studies on diurnal and seasonal plant–water relations in crop provide an understanding of the response of the crop and adaptation to moisture stress by regulating water vapor loss and internal water status. Relationships between the indices of plant–water relation may vary with the following:

- Species
- Stage of development
- Time of the day
- Evaporative demand
- Plant-water history

5.7.2 Indices of Plant–Water Relations

The commonly used indices for plant-water status are:

- Water content or water retention capacity
- Relative water content
- Relative saturation deficit
- Leaf water potential
- Osmotic potential

Typically, water potential is expressed in units of pressure, with the most common units being bars or mega-pascals (MPa). One mega-pascals is equal to 10 bars.

5.7.3 Water Potential in Plant

5.7.3.1 Components of Water Potential

The potential value can be positive or negative. Water potential in plant cells has several components. The most important are osmotic potential and turgor (pressure) potential. These two potentials sum up and together equal total water potential, i.e.,

$$\text{Total water potential of a plant}: \psi_{\mathrm{t}} = \psi_{\mathrm{os}} + \psi_{\mathrm{p}}, \tag{5.5}$$

where ψ_{t} is the total water potential, ψ_{os} is the osmotic potential, and ψ_{p} is the turgor or pressure potential.

5.7.3.2 Osmotic Potential

Osmotic potential is due to the presence of dissolved solutes (e.g., sugars, salts) in the water. When a solute is dissolved in water it lowers the osmotic potential. Since pure water (nothing dissolved in it) has a water potential of zero, adding salt or some other solute will result in a negative water potential. An osmometer demonstrates this principle very well.

5.7.3.3 Turgor Potential

Turgor (or pressure) potential results when pressure is applied to the water. For example, if a tank of water is pressurized, its water potential can be raised above zero. Living plant cells typically have positive turgor potential, and osmotic and turgor potential often work to balance each other. When you see wilted leaves they have zero turgor potential. In the dead xylem of trees, water often has a negative turgor pressure and we say it is "under tension".

Water potential varied diurnally, with minimum values around noon, and increasing in the late afternoon and evening to maximum values before dawn.

5.7.3.4 Factors Affecting Plant Water Potential

Factors that determine plant water potential are:

1. *Amount of solutes*: Increasing concentrations will lower the free energy (water potential); termed osmotic potential (ψ_{s}).
2. *Turgor pressure* (ψ_{p}) *in plant cell*: Positive pressure inside plant cell increases free energy.

5.7.3.5 Adjustment of Plant–Water Relations Components

To maintain water uptake from the soil, plants must maintain a lower water potential, but minimize water loss. Plant water potential can be altered by the following:

1) Osmotic adjustment – increasing osmotic potential as soils dry
2) Changes in cell wall elasticity – determines how much turgor pressure will change as cell water content changes.

Different techniques are used to determine plant–water relations parameters that are indicative of plant water status. Plant–water relation parameters vary substantially during the day and because of water stress (drought, dehydration, osmotic, etc.).

5.7.4 *Leaf Water Potential*

5.7.4.1 Total Leaf Water Potential

Similar to water potential of other plant cells, leaf water potential (ψ) is commonly resolved into two components, the mean pressure potential or turgor (ψ_{p}) and the mean solute potential or osmotic potential of the vacuolar contents (ψ_{os}):

$$\psi = \psi_{\mathrm{p}} + \psi_{\mathrm{os}}$$

ψ may be measured by a wide range of methods. Psychrometric techniques permit non-destructive measurement of ψ, by contrast both ψ_{os} and ψ_{p} have usually been measured destructively.

Osmotic pressure (or osmotic potential) is a measure of the attraction of solutes for water. It is defined as the hydrostatic pressure that must be applied to a solution to prevent water flowing into it when it is separated from pure water by a membrane that allows the passage of water. It is a colligated property, that is, its value depends simply on the number of solute molecules present.

Accurate measurements of leaf water potential (ψ) in the field are essential for studying crop responses to water stress. Water is normally under tension (negative pressure) in the stems of trees and to get water out great pressure needs to be applied. A tool called a "*pressure chamber*" or "*pressure bomb*" is often used by plant scientist to measure this tension. The Scholander pressure chamber (also referred to as Plant Water Console) (Fig. 5.7) is the most widely used apparatus for ψ measurement, although thermocouple psychrometers are generally accepted as the standard.

Fig. 5.7 View of a plant water console (*Courtesy*: Soilmoisture Co.)

Procedure for Estimation of Total Leaf Water Potential

The measurement of water potential of leaf xylem is made between 11:30 and 14:00 h. Single leaflets' are enclosed in a plastic bag immediately prior to detachment from the plant in order to minimize subsequent evaporative losses. A single leaf (leafy shoot or needle fascicle) is sealed in the pressure chamber with the cut surface protruding through a rubber stopper visible to the experimenter. Pressure is applied to the shoot from a tank of compressed air (or nitrogen) until xylem sap just appears at the cut ends of the xylem elements. At that instant, the hydrostatic pressure inside the xylem elements is exactly balanced by the applied external pressure, and the chamber pressure is recorded. The amount of pressure that must be applied to force water out of the leaf cells into the xylem is regarded as equal (and opposite) to the tension originally existing in the xylem at the time the leaf was separated from the plant. This value is an estimate of the water potential, expressed in negative (−) units by convention.

The leaf-water potential of water-stressed plant may develop as high as −25 bars. Some stress corresponding to leaf-water potential of −5 bars in wheat crop is not detrimental for yield.

5.7.4.2 Leaf Osmotic Potential

Leaf osmotic potential can be measured on expressed sap by freezing point depression osmometry using osmometer or dew point hygrometer. Leaflets are detached and rapidly frozen with liquid nitrogen. About 24 h later, the samples are thawed at room temperature for half an hour before the samples are crushed to provide several millimeters of sap. The sap is placed in osmometer with a plastic syringe and the reading is taken.

5.7.4.3 Turgor Pressure

Turgor pressure (ψ_{p}) is obtained as the difference between leaf water potential (ψ_{L}) and leaf osmotic potential (ψ_{s}) determined with separate leaflets from the same leaf.

5.7.5 Water Content/Water Retention

The water content/retention of a leaf (WC),

$$\mathrm{WC}(\%) = 100 \times \frac{\text{fresh wt.} - \text{dry wt.}}{\text{fresh wt.}}. \tag{5.6}$$

The drought resistant cultivars showed greater water retaining ability than the drought susceptible cultivars.

The measurement of water retention is simple and rapid, as it requires only weighing each leaf sample twice. If one is dealing with lines that vary considerably in their water retention ability (under a specific soil water or drought condition), no special care is required to control the drying condition if all the samples are allowed to dry on the same bench or setting condition.

5.7.6 Relative Water Content/Relative Turgidity

Water content of a plant part is defined as the amount of water contained per unit of dry weight of that part.

Relative water content (RWC) is defined as:

$$\mathrm{RWC} = \frac{\text{Fresh wt.} - \text{dry wt.}}{\text{Turgid fresh wt.} - \text{dry wt.}} \tag{5.7}$$

The value is often expressed in percentage form.

There is evidence that, for some physiological processes, relative water content may be a more relevant measure of stress than ψ, though the later may be measured more easily.

5.7.6.1 Procedure for the Measurement of Relative Water Content

(a) Measure the fresh weight and record it. The leaves are weighed immediately after collection (in a digital balance, preferably having 3–4 digit after decimal point) to obtain fresh weight. For accuracy, measurement in the field is preferred. If the facility is not available, insert the leaf in the polythene packet just after detaching from the plant, and put in a closed box (such as in an ice box) and carry to the lab for measurement.

(b) Float the leaf sample on water in a petri-dish overnight, or put the cutting edge of the leaf on water in a cylinder, close the cylinder to eliminate evaporation and place it in dark place for about 6–10 h.
(c) Then remove the leaf from the water, sweep the water from the leaf with dry tissue paper gently (do not damage the leaf), and quickly measure its weight on a balance. Next, place the leaf in a labeled paper bag and set it on the tray.
(d) To obtain the dry weight, place the samples (with leaf ID) in a 70°C oven to completely dry (for about 24–48 h).
(e) Take weight of the samples immediately after taking out of the oven (if it is delayed to take weight, the leaves can absorb water from the surrounding moist air).
(f) Calculate the RWC using the formula given above.

5.7.7 Relative Saturation Deficit

Relative saturation deficit (RSD):

$$\text{RSD} = 100 \times (\text{saturated wt.} - \text{fresh wt.})/\text{saturated wt.} \tag{5.8}$$

5.7.7.1 Determination of RSD

The youngest, fully expanded leaf is collected. The fresh and saturated weight of the leaf can be obtained following the procedure as of *Relative Water Content*. Then the RSD is calculated from the above formula.

The RSD increases with a corresponding decrease in water content.

5.7.8 Relation Between Leaf Water Potential and Relative Water Content

Relation between leaf water potential and relative water content can be determined using following procedure. After the saturation weight of the leaf is obtained, the leaf is allowed to dry under ambient conditions in the laboratory. At periodic intervals (1/2–1 h interval for about 12 h), leaf water potential is measured soon after determining fresh weight. After the end of measurements, the leaf is dried at 80°C and weighed. The relationship can be expressed in two ways:

(a) Leaf water potential vs. relative water content, also termed as pressure–volume curve
(b) Reciprocal of leaf water potential (LWP) vs. relative water content (RWC)

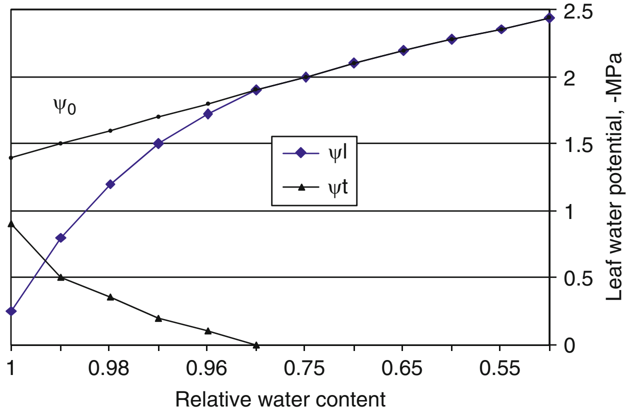


Fig. 5.8 Pressure volume curve

5.7.8.1 Leaf Water Potential vs. Relative Water Content

The curve showing the relationship between the water potential of an organism, in general the leaf, and its relative water content, is termed as the pressure–volume curve. The graphical analysis of the curve yields several water parameters.

The pressure volume curve typically has two parts. In the first part, turgor (ψ_t) and osmotic potential (ψ_o) are combined (Fig. 5.8). As the turgor potential falls to zero with decreased leaf water potential, the relationship becomes linear and represents only the osmotic potential at that relative water content. Extrapolation yields an estimate of the osmotic potential for maximum relative water content. From the extrapolated values of the osmotic and the observed values of the leaf water potential (ψ_l), the turgor potential (ψ_t) can be calculated as follows:

$$\psi_t = \psi_l - \psi_o$$

5.8 Plant Biochemical and Physiological Aspects

5.8.1 Plant Biochemical Aspects

5.8.1.1 Photosynthesis

Photosynthesis is a complicated biochemical process. Plants use light as their energy source. The general equation for photosynthesis is:

$$CO_2 + H_2O + \text{light} \rightarrow (CH_2O)_n + O_2 \qquad (5.9)$$

Leaves are perfect solar collectors. These organs are broad and flat to allow for efficient light harvest. The leaves are broad to maximize surface area for light harvest and they are thin since light cannot penetrate too deeply into the leaf (the amount of light decreases exponentially with distance). Within the thin leaf, most chloroplasts are found in the upper layer of cells, the palisade layer, which is the tissue layer just beneath the upper epidermis.

Photosynthesis requires the following:

- Efficient light harvesting
- An apparatus for gas exchange
- A water supply
- Thin leaves, required for light absorption and gas exchange, need support
- A mechanism to transport end products throughout the plant

5.8.1.2 Leaf Chlorophyll and Sugar Content

Chlorophyll content can be determined from the leaf samples following the method of Arnon (1975) and Coombs et al. (1985). Reducing sugar can be determined following Somogyi–Nelsen method (Nelsen 1944; Somogyi 1952).

5.8.2 Physiological Aspects

5.8.2.1 Transpiration Rate

Transpiration can be defined as the loss of water from plants in the form of vapor. A plant of vigorous growth transpires heavily. The velocity of solute transport increases and falls with the rate of transpiration. Transpiration causes evaporative cooling of the leaf.

Control of Transpiration

The opening and closing of stomata is the principal factor controlling transpiration rate. The closure of stomata is influenced by light intensity, temperature, and atmospheric CO_2 concentration. Stomata closure is also influenced by tissue hydration, and more specifically, by the turgidity of the paired guard cells. Increasing turgidity causes these cells to bulge outwards, while low turgidity causes them to collapse against each other, thus shutting off the diffusive outlet for the water vapor. The turgidity of the cell is governed by the availability of water to plant, which in turn governed by the soil-water availability or soil-water content. In essence, the transpiration rate is controlled by the following:

- Light intensity
- Temperature

- Atmospheric vapor pressure deficit (at plant canopy level)
- Atmospheric CO_2 concentration
- Soil water availability (under saline condition) *or* soil water content (under drought condition)

Measurement of Transpiration Rate

Transpiration is commonly measured by (a) gravimetric methods, (b) measuring humidity increase in a plastic cuvette that completely encloses the leaf or stem, or (c) estimating the velocity of sap flow.

Transpiration Estimates by Gravimetric Method

Transpiration estimates by a gravimetric approach involves measuring plant weight at several intervals of time and then estimating the mass of water loss per unit leaf area per unit time. Transpiration rates is to be recorded at 15-min intervals throughout the day (completion of last period).

Procedure:

1. Take a waterproof container of plant. Carefully wrap the container in a plastic bag and secure with a rubber band so the measurement does not reflect any water loss from the soil surface, i.e., prevent evaporation. Care should be taken so that no injury occurs in the stem during the process, and note that plants will require a period to “adapt” to the wrapping procedure.
2. Place the container in open place.
3. Take weight of the container after several hours interval.
4. Obtain a water loss rate for each plant (g H_2O min^{-1}) from the difference in weight.
5. Measure the total leaf surface area for each plant separately using a Leaf Area Meter.
6. Compute a transpiration rate (mmol H_2O m^{-2} s^{-1}) by dividing the weight loss to the total leaf area.

Necessary conversion factors:

$$1\text{g } H_2O = 55.55 \text{ mmol};\ 1 \text{ m}^2 = 10{,}000 \text{ cm}^2;\ 1 \text{ h} = 3{,}600\,\text{s}$$

Data sheet for determination of transpiration rate by the gravimetric method for each plant of each treatment

Treatment/plant	Water loss rate (g min^{-1})	Water loss rate (mmol H_2O s^{-1})	Leaf area (m^2)	Transpiration rate (mmol H_2O m^{-2} s^{-1})
Plant 1				

5.8.2.2 Respiration

Respiration in plants is essential to provide metabolic energy and carbon skeletons for growth and development, and an essential component of a plant's carbon budget. It consumes about 25–30% of all the carbohydrates produced in photosynthesis. Recent study showed that photo-respiration enables the plant to take inorganic nitrogen in the form of nitrate and convert it into a form that is useful for plant growth (David 2010).

5.9 Water and Nutrient Uptake

5.9.1 Water Uptake Theory

The issue of water flow through the root zone of field crops represents a complex problem requiring knowledge of a large spectrum of phenomena from various disciplines. Within the state of the art, two theories of water absorption are available:

- Active absorption
- Passive absorption

5.9.1.1 Active Absorption

Active absorption is operating in slowly transpiring plant. Under favorable conditions, root systems function as osmometers. According to this theory, accumulation of salt in the root xylem sap lowers the water potential below that in the soil. The resulting inward diffusion of water produces the "root pressure," which transmitted to the evaporating surface of the leaf.

5.9.1.2 Passive Absorption

Passive absorption is operating when transpiration is rapid. According to this theory, roots operate simply as passive absorbing surface. Evaporation of water from the leaf cells (transpiration) lowers the cell water potential and causes movement of water into them from the xylem, thus reducing the pressure in the xylem sap. The reduction in pressure of the xylem sap is transmitted to the roots, reducing the water potential and causing mass inflow of water from the soil, unless of course the soil is at a more negative water potential. The resulting tension or suction induces upward mass flow from roots to leaves through the tube like capillary vessels of the xylem. These capillary vessels can maintain the cohesive continuity of liquid water columns even under a tension of many bars, as needed to draw water from relatively dry soils and transport it to the top of the tree.

The roots therefore merely acts as passive absorbing surfaces through which water is pulled by a gradient of water potential generated in the transpiring shoots. This theory is also termed as "cohesion-tension theory." As one water molecule evaporates from the leaf, another is pulled in and so on down the stem. The drier the soil, the more tension is required to pull water in from the soil. When the soil is moist (water potential close to zero), water flows easily into the root and up the stem.

5.9.2 Nutrient Uptake

The key-role of fertilizers and their judicious use in crop husbandry is well understood, when one is familiar with the general facts about plant nutrition. It is now known that at least 16 plant-food elements are necessary for the growth of green plants. These plant-nutrients are called essential elements. In the absence of any one of these essential elements, a plant fails to complete its life cycle, though the disorder caused can, however, be corrected by the addition of that element. These 16 elements are: Carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorous (P), sulphur (S), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mb), boron (B), and chlorine (Cl). Green plants obtain carbon from carbon-di-oxide from the air; oxygen and hydrogen from water, whereas the remaining elements are taken from the soil. Based on their relative amounts, normally found in plants, the plant nutrients are termed as macronutrients, if large amounts are involved, and micronutrients, if only traces are involved. The micronutrients essential for plant growth are iron, manganese, copper, zinc, boron, molybdenum, and chlorine. All other essential elements listed above are macronutrients.

As mentioned above, most of the plant nutrients, besides carbon, hydrogen, and oxygen, originate from the soil. In the soil system, the nutrients are viewed by the soil scientists as a triple-phased system of solid, liquid, and a gaseous phase. These phases are physically separable. The plant nutrients are based in the solid phase and their usual pathway to the plant system is through the surrounding liquid phase, the soil solution and then to the plant root and plant cells. This pathway may be written in the form of an equation as follows:

$$\mathrm{M(Solid)} \rightarrow \mathrm{M(Solution)} \rightarrow \mathrm{M(Plant\ root)} \rightarrow \mathrm{M(Plant\ top)}$$

where "M" is the plant nutrient element in continual movement through the soil-plant system.

The operation of the above system is dependent on the solar energy through photosynthesis and metabolic activities. This is however, an oversimplified statement for gaining a physical concept of the natural phenomenon, but one should bear in mind that there are many physical and physico-chemical processes influencing the reactions in the pathway. The actual transfer in nature takes place through the charged ions, the usual form in which plant-food elements occur in solutions (liquid phase of the system). Plant roots take up plant-food elements from the soil in these ionic forms. The positively charged ions are called "cations" which include potassium (K^+), Calcium (Ca^{++}), magnesium (Mg^{++}), iron (Fe^{+++}), zinc (Zn^{++}), and so on. The negatively charged ions are called anions and the important plant nutrients taken in this form include nitrogen ($NO^-{}_3$), phosphorous ($H_2PO^-{}_4$), sulphur ($SO^-{}_4$), Chlorine (Cl), etc.

The process of nutrient uptake by plants refers to the transfer of the nutrient ions across the soil root interfaces into the plant cell. The energy for the process is provided by the metabolic activity of the plant and in its absence no absorption of nutrients take place. Nutrient absorption involves the phenomenon of ion exchange. The root surface, like soil, carries a negative charge, and exhibits cation-exchange property. The most efficient absorption of the plant nutrients takes place on the younger tissues of the roots, capable of growth and elongation.

In this respect, root-systems are known to vary from crop to crop. Hence their feeding power differs. The extent and the spread of the effective root-system determine the soil volume trapped in the feeding-zone of the crop plant. This is indeed an important information in a given soil–plant system which helps us to choose fertilizers and fertilizer-use practices. The nutrient absorption mechanisms of the crop plants are fairly known now. There are three mechanisms in operation in the soil–water–plant systems. They are as follows:

1. The contact exchange and root interception
2. The mass flow or convection
3. Diffusion

5.9.2.1 The Contact Exchange and Root Interception

In the case of contact exchange and root interception, the exchangeable nutrients ions from the clay-humus colloids migrates directly to the root surface through contact exchange when plant roots come into contact with the soil solids. Nutrient absorption through this mechanism is, however, insignificant as most of the plant nutrients occur in the soil solutions. Plant roots actually grow to come into contact with about only 3% of the soil volume exploited by the root mass, and the nutrient uptake through root interception is even still less.

5.9.2.2 Mass Flow or Convection

The second mechanism is mass flow or convection, which is considered to be the important mode of nutrient uptake. This mechanism relates to nutrient mobility with the movement of soil water toward the root surface where absorption through the roots takes place along with water. Some are called mobile nutrients. Others which move only a few millimeters are called immobile nutrients. Nutrient ions such as nitrate, chloride, and sulfate are not absorbed by the soil colloids and are mainly in solution. Such nutrient ions are absorbed by the roots along with soil water. The nutrient uptake through this mechanism is directly related to the amount of water used by the plants (transpiration).

It may, however, be mentioned that the exchangeable nutrient cations and anions other than nitrate, chloride, and sulfate, which are absorbed on soil colloids are in equilibrium with the soil solution do not move freely with water when it is absorbed by the plant roots. These considerations, therefore, bring out that there are large differences in the transport and root absorption of various ion through the mechanism of mass flow. Mass flow is, however, responsible for supplying the root with much of the plant needs for nitrogen, calcium, and magnesium, when present in high concentrations in the soil solution, but does not do so in the case of phosphorous or potassium. The nutrient uptake through mass flow is largely dependent on the moisture status of the soil and is highly influenced by the soil physical properties controlling the movement of soil water.

5.9.2.3 Diffusion

The third mechanism is diffusion. It is an important phenomenon by which ions in the soil medium move from a point of higher concentration to a point of lower concentration. In other words, the mechanism enables the movement of the nutrients ion without the movement of water. The amount of nutrient-ion movement in this case is dependent on the ion-concentration gradient and transport pathways which, in turn, are highly influenced by the content of soil water. This mechanism is predominant in supplying most of the phosphorous and potassium to plant roots. It is important to note that the rhizosphere volume of soil in the immediate neighborhood of the effective plant root receives plant nutrients continuously to be delivered to the roots by diffusion. However, when the nutrient concentration builds up far excess of the plant in the reverse direction. These are some of the choice of fertilizers and fertilizer practices for practicing scientific agriculture.

5.10 Critical Growth Stages of Plant and Water Demand for Whole Growth Period

5.10.1 Critical Growth Stages

All the growth stages of plants are not similar in their response to water deficit. Critical stages are the growth stages when the plants are most sensitive to water deficit or stress.

The response of plants to water deficits and the interaction with the variable environment is complex because conditions vary with the frequency of deficit or drought and wet periods, the sequence of deficit, the degree of deficit, the speed of onset of deficit, and the patterns of soil-water deficits and/or atmospheric-water deficits. In a slowly developing stress condition, the plants can adapt the stress by osmotic adjustment. But the plants can have little osmotic adjustment to rapid development of stress.

In most cereal crops, the early growth stage and anthesis stage of growth are the most sensitive to water stress.

5.10.2 Water Demand

Water demand of common field crops is cited below (Table 5.4):

5.11 Plant Adaptation to Stress/Drought: Stress Physiology

5.11.1 Mechanisms of Plant Survival

The overall ability of a plant to survive in a drought depends on many morphological, physiological, and phenological characteristics. The mechanisms are categorized here, but it needs to be emphasized that these categories are not mutually exclusive and it is the interaction of many factors that result in the overall ability to cope with a drought.

Drought avoider: Active life cycle occurs when water is available.
Drought tolerator: Growth occurs when drought can be expected (most trees).
Dessication Postponement: Mechanisms which slow water loss or increase uptake (most trees).
Dessication tolerance: Ability to withstand desiccation and recover when water is again available.

Table 5.4 Crop duration and water demand of some common field crops

Crop	Duration (days)	Total water demand (cm)	Irrigation frequency (nos.)
Rice	120–150	120–160	10–15
Wheat (winter)	120–130	25–35	4–7
Wheat (spring)	155–165	40–60	10–12
Maize	120–130	30–40	6–7
Pulses	100–120	15–30	3–5
Vegetable	70–90	15–20	3–5

5.11.1.1 Drought Avoider

Some plants can be classified as drought avoiders. These are plants that complete their entire active life cycle during a period where drought does not occur. Typically these are plants that grow in dessert regions with well-defined rainy seasons. During the rainy season the seeds sprout, the plant matures, flowers, and develops new seed before the next often prolonged dry season. Increased stomatal resistance, direct absorption of water by hairy leaves and leaf rolling also contribute to drought avoidance. Drought semi-deciduous species avoid excessive water loss with a reduction of their transpiring surface through partial fall of leaves during the dry period.

5.11.1.2 Drought Tolerator

Most tree species fall into the category of drought tolerators. These are plants which have portions of their active life cycles during periods when drought can be expected. Drought tolerance can be broken down into two subcategories – desiccation postponement and desiccation tolerance. Desiccation postponement mechanisms prevent the loss of water out of the plant or increase the rate of water uptake into the plant, in this way they postpone desiccation during a drought. Many tree species utilize avoidance mechanisms. These mechanisms might involve:

1. Deep, wide spreading root systems.
2. Rapid stomatal closure during the onset of drought.
3. Smaller leaf size.
4. Metabolic adaptations to avoid water loss.
5. Water storage in pant organs (e.g., trunk) and in extreme cases.
6. Leaf abscission to prevent further water loss. All of these mechanisms can occur as adaptations and many acclimations.

5.11.1.3 Desiccation Tolerance

Desiccation tolerance is the ability of plants to desiccate but still survive. Most tree species do not do this well. If leaves and other living tissues actually desiccate, they typically become damaged or even killed. However, some plants such as grasses and mosses can become severely desiccated and upon rehydration resume growth. Tree species, however, will often osmotically adjust in response to a drought. Osmotic adjustment is an acclimation where the plant lowers its osmotic potential in response to a drought and in this way maintain turgor despite a lower water potential. In a way the plant is desiccating as indicated by the lower water potential but at the same time it maintains its turgor.

5.11.1.4 Dehydration Tolerance

The improved dehydration tolerance of the summer leaves are attributed to possession of physiological and/or biophysical adaptations to water stress, which are reflected in lower osmotic potential at full turgor and osmotic potential at turgor loss point.

5.11.2 Drought Tolerance Mechanism

Drought is a meteorological event which can be defined as a period without rainfall of sufficient duration that plant growth is impacted negatively. Most plants, and particularly tree species since they are so long-lived, are exposed to drought during their lifetime. In order to minimize the impact, and during severe drought, survive, plants must have mechanisms in place to cope with the drought.

At this point we should differentiate between the terms *adaptation* and *acclimation*. Some plants are better adapted to cope with a drought. Others aren't very drought hardy but they can be acclimated to perform better. Adaptations are characteristics which are heritable or passed on from generation to generation. They are genetically based and the parent will pass on the adaptation to their offspring. An example of this could be the potential of a particular species or genotype to produce a deep and wide-spreading root system. Regardless of where the tree is planted it will produce a deep and wide-spreading root system.

An acclimation on the other hand is a modification of a characteristic in response to the environment. An example of this is the ability of a species to change the morphology of its root system in response to the environment. The root system is deep and wide spreading when the tree is planted on a dry site, but shallow when planted on a wet site.

5.11.2.1 Adaptive Response

There are many different ways of adaptation to drought. These are concerned with long-term changes in morphology and allocation to root, and short-term changes in physiological characteristics of leaves. Common adaptive responses of herbaceous annuals to water stress include the following:

- Increasing osmotic potential of leaves/osmotic adjustment
- Increases in root density
- Deeper root
- Rapid development to escape drought
- Temporal leaf fall
- Thinner leaves (and their density and specific leaf mass are higher)

5.11.2.2 Osmotic Adjustment

The term "osmotic adjustment" originated in the salinity literature to describe a change in the osmotic pressure of leaves in parallel with that of the soil. An increase in the osmotic pressure of leaves or roots, due mainly to salts, is considered an "adjustment" to the increase in the salt concentration in the soil. Osmotic adjustment is usually defined as an increase in osmotic pressure of cell sap resulting from more solute molecules per cell rather than from a lower cell volume. Osmotic adjustment has emerged as a unified concept in stress hydrology. Many plants undergo osmotic adjustment (erroneously called "osmoregulation") by accumulating ions and organic solutes when exposed to drought or salt stress.

Osmotic adjustment plays a role in maintenance of a leaf water status favorable for some growth in water-stressed leaves. Osmotic adjustment through active accumulation of solutes as well as an increase of solute concentration through reduced cell volume (elastic adjustment) can result in turgor maintenance. Due to osmotic adjustment, the plants are able to maintain turgor potential at a similar level for lower values of leaf water potential. Mild water stress (approximately soil water potential of -5 bars) at critical growth stages of cereals, the plants could maintain positive turgor almost at the level of plants suffering no soil water stress, through osmotic adjustment.

Two types of osmotic adjustment may occur:

1. The first corresponds with the phenological development of the plant (agronomic aspects).
2. The second is achieved by physiological adaptation to drought or salinity (physiological aspects).

Physiological adjustments enable the plant in a saline or drought environment to maintain the turgor potential at a similar level as under non-saline or non-drought conditions. The agronomic consequences are that plants show a slight decrease in evapotranspiration and yield due to salinity or water stress, which may be caused by the decrease in leaf area and the maintenance of gaseous exchange under saline conditions.

The degree of osmotic adjustment varies with:

- Cultivar
- Age of the tissue
- Rate and pattern of the development of stress

Greater osmotic adjustment is observed with slow, compared with more rapid rates of stress development. Exposure to two periods of drought increases the magnitude of the osmotic adjustment compared with that after one period of drought. Field-grown crops show increased osmotic adjustment compared with pot-grown seedlings.

Chemicals in Osmotic Potential

Of the various solutes present in cell sap of mesophytes, potassium is a major components of the osmotic potential and play an important role in osmotic regulation of elongating cells, as well as specialized functions such as stomatal guard cells and motor cells. Organic solutes such as sugars and amino acids are also major components, with the relative contribution depending on cultural conditions. In expanded leaves of wheat that ware subjected to water stress, changes in potassium, sugar and amino acids (including proline) accounted for 90–100% of the changes in the osmotic potential.

Determination of Osmotic Adjustment

Osmotic adjustment can be determined by the difference in osmotic potential at full turgor between stress and non-stress plants, after re-hydrating the stress plants for 6 h in the light.

5.11.2.3 Other Reason/Mechanism for Plant Adaptation

Stress Preconditioning

The leaf water potential (ψ_l) vs. relative water content (RWC) relationship is altered as a result of stress preconditioning. Under water stressed situation, at a given ψ_l, stress preconditioned plants maintain a higher tissue water content than that of an unconditioned plants. Furthermore, the capacity to maintain a relatively high water content at a given ψ_l value increases with the severity of stress preconditioning. Transpiration in pre-stressed plants shows less sensitivity to the alteration of ψ_l than in the non-stressed plants.

5.11.3 Yield Estimation Under Drought Condition

Yield under drought (Y_d) can be estimated as (adapted from Hiler and Clark 1971):

$$Y_d = Y_p(1 - \mathrm{SD}), \tag{5.10}$$

where Y_d is the yield under drought, Y_p is the potential yield, and SD is the drought sensitivity or drought susceptibility of the crop.

Drought susceptibility should be determined experimentally as follows:

$$\mathrm{SD}_i = \frac{Y - Y_i}{Y}$$

Where, Y is the yield from plots without any moisture stress, Y_i is the yield with moisture stress in stage i, SD_i is drought sensitivity caused by stress during the growing stage i.

The model mostly used is the one proposed by Stewart and Hagan (1973):

$$Y = Y_\mathrm{m} - Y_\mathrm{m} \cdot K_y \cdot \mathrm{ETD}/\mathrm{ET}_\mathrm{m}, \tag{5.11}$$

In which Y is the crop yield; Y_m is the maximum crop yield under the same condition of soil texture, fertility, etc.; K_y is the crop coefficient; ETD is the cumulative evapotranspiration deficit during the growth period, calculated as follows: $\mathrm{ETD} = \mathrm{ET}_\mathrm{m} - \mathrm{ET}_\mathrm{a}$, in which $\mathrm{ET}_\mathrm{m}$is the maximum evapotranspiration and ET_a is the actual evapotranspiration.

Stewart et al. (1977) proposed a model that takes into account the effect of moisture stress during successive phenological stages. They used a different coefficient for each stage, according to the following equation:

$$\frac{Y}{Y_\mathrm{m}} = \prod_{n=1}^{m} \left[1 - k_{y_n}\left(1 - \frac{\mathrm{ET}}{\mathrm{ET}_\mathrm{m}}\right)_n\right] \tag{5.12}$$

where n is generic growth stage, and m is the number of growth stage considered, and k_y is the crop or yield response factor. The formula is based on the theory that, considering all other factors of production at their optimum level, it is the water scarcity factor (estimated as the ratio of actual to maximum evapotranspiration, $\mathrm{ET}/\mathrm{ET}_\mathrm{m}$) that limit the final yield.

5.12 Plant Production Models

Various plant production models exist with varying levels of utility (cell, physiological, individual plant, crop, geographical region, global) and of generality. A model can be crop-specific or be more generally applicable. The United States Department of Agriculture has sponsored a number of applicable crop growth models for various major US crops, such as cotton, soybean, wheat and rice. Other widely-used models are APSIM, Cropsyst, CERES, PLANTGRO, ORYZA2000, SUCROS (SWATR), SUBSTOR, the FAO-sponsored CROPWAT, AGWATER, and the erosion-specific model EPIC.

5.12.1 APSIM

APSIM stands for "Agricultural Production Systems sIMulator." The APSIM is a modeling framework that provides capabilities to simulate cropping systems over variable time periods using available meteorological data (Keating et al. 2003). The framework provides a "plug-in-pull-out" facility allowing users to select modules for modeling crop and their environments under a range of constraint conditions. APSIM allow the coupling of models from separate research efforts. APSIM allows the simulation of diverse crops and cropping systems targeting issues such as nitrogen management, climate variability, land degradation, crop rotations, and management alternatives.

5.12.2 CropSyst

CropSyst is a multi-year multi-crop daily time step simulation model (Stockle and Nelson 1994). The model has been developed to serve as an analytical tool to study the effect of cropping systems management on productivity and the environment. The model simulates the soil-water budget, soil-plant nitrogen budget, crop canopy and root growth, dry-matter production, yield, residue production and decomposition, and erosion. Management options include cultivar selection, crop rotation (including fallow year), irrigation, nitrogen fertilization, tillage operations, and residue management.

5.12.3 Oryza2000

The ORYZA2000 rice growth model has been developed at the IRRI in cooperation with Wageningen Agricultural University. This model, too, is programmed in FORTRAN. The scope of this model is limited to rice, which is the main food crop for Asia.

5.12.4 SUCROS

SUCROS is programmed in the Fortran computer programming language. The model can and has been applied to a variety of weather regimes and crops. Because the source code of Sucros is open source, the model is open to modifications of users with FORTRAN programming experience. The official maintained version of SUCROS comes into two flavors: SUCROS I, which has non-inhibited unlimited crop growth (which means that only solar radiation and temperature determine growth) and SUCROS II, in which crop growth is limited only by water shortage.

Relevant Journals

- Plant Physiology (Springer)
- Australian Journal of Plant Physiology
- Annual Revew of Plant Physiology
- Australian Journal of Biological Science
- New Phytology
- Journal of Experimental Botany
- Crop Science
- Field Crop Research
- American Journal of Botany
- Botanical Review
- Plant and Soil
- Physiology of Plant
- Botanical Gazette
- Faraday Society Discussion
- Planta
- Arid Zone Research
- Journal of Applied Ecology
- Science
- Indian Journal of Plant Physiology (now, Plant Physiology)
- Annals of Plant Physiology
- Advances in Plant Physiology
- Agronomy Journal
- Advances in Agronomy

Questions

1. Classify plants considering various aspects.
2. What are the most common growth stages of cereal crops?
3. Describe different numerical scales for growth stages of field crops.
4. Briefly discuss the growth and development of wheat plant.
5. Describe the equation expressing cereal yield as the product of yield components.
6. What do you mean by critical growth of crop? Name the critical growth stages of wheat plant.
7. What is thermal time for crop growth?

8. What are the functions of root? Describe the growth and development of crop root.
9. Briefly narrate the factors affecting root development and adaptation to stress condition.
10. Discuss the norms and procedures of drymatter partitioning in plants.
11. What are the indicators of drymatter partitioning? Write the equation for adjusting crop grain moisture to a particular level.
12. How the assimilate partitioning to grain can be improved?
13. Write short note on: LAI, SLA, RGR, RLD, growth rate.
14. Explain different methods of root sampling and rootmeasurement.
15. How the available water for plants can be increased?
16. Briefly discuss the different plant–water relation indicators.
17. What are the components of plant water potential? What are the factors affecting plant water potential?
18. What is pressure–volume curve? Draw a sketch of pressure–volume curve.
19. What are the factors limiting transpiration in plant?
20. Briefly explain the available theories of plant water uptake.
21. What are the mechanisms of plant survival under stress condition?
22. How the yield is decreased under stress conditon?
23. Name some crop growth and yield model, and explain their utility in brief.

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Chapter 6
Water: An Element of Irrigation

Water is the source of all life on earth. Water has many unique properties that allow it to be such a universal material. One special characteristic of water is its ability to change state very easily under earth conditions. These forms play a great part in the hydrologic cycle. For irrigation, a typical characteristic of water (termed as "water quality") is important. This "characteristic" feature influences the suitability of water for an intended use. To irrigate in a sustainable fashion, it is important to assess the water quality characteristics, land suitability, and crop limitations. Even water of reasonable quality may negatively affect the soil if salinity levels concentrate over time.

Water quality for intended use can be evaluated with a water quality test. Understanding of the basic chemistry of water quality parameters is an essential first step in making good measurements. Water quality standards are the foundation of the water quality-based pollution control program. A range of management strategies of varying complexities are available to mitigate the effects of poor quality water. Present scientific knowledge, if judiciously applied, may be adequate for coping with many quality problems resulting from mismanagement of agricultural inputs, irrigation, and drainage.

6.1 Sources and Uses of Water

Water covers about 70% of the earth's surface, but it is difficult to comprehend the total amount of water when we only see a small portion of it. The oceans contain about 97.5% of the earth's water, land 2.4%, and the atmosphere holds less than 0.001%, which may seem surprising because water plays such an important role in weather. The annual precipitation for the earth is more than 30 times the atmosphere's total capacity to hold water. This fact indicates the rapid recycling of water that must occur between the earth's surface and the atmosphere.

Basically, the source of all water in the earth is rainwater. Conceptually, the main sources of water from where we meet our needs are the following:

M.H. Ali, *Fundamentals of Irrigation and On-farm Water Management: Volume 1*,
DOI 10.1007/978-1-4419-6335-2_6,

1. Surface water - from rivers, ponds, lakes, etc.
2. Ground water - through dug wells, shallow tube-wells, deep tube-wells, springs, etc.
3. Rain water - from direct rainfall, rain water harvesting.

Water is essential to life. Without it, the biosphere that exists on the surface of the earth would not be possible. Besides consumptions of biosphere, water resources are harnessed for drinking, irrigation, municipal and industrial uses, hydropower generation, fish farming, flood management, navigation, ecological needs, and recreation.

6.2 Special Characteristics of Water

Water has no close substitutes or replacements. It can not be produced or manufactured economically on demand. The natural distribution of water, however, is quite varied. Many locations have plenty of it while others have very little. Water has many unique properties that allow it to be such a universal material. One special characteristic of water is its ability to change state very easily under earth conditions. It can be found readily on the planet in all of its three forms: solid (ice), liquid, and gas (water vapor). These forms play a great part in the hydrologic cycle. It has high latent and specific heats, expansion during freezing, high surface tension, and viscosity, and effectiveness as a solvent. Liquid water consists of molecules held together by hydrogen bonding, while in ice, the molecules are arranged in a rigid lattice.

Among the many elements essential to abundant and efficient food and fiber production, water occupies a singular place. First, it is productive machinery of crop plants. Second, in contrast with many manufacturing processes, the water used cannot ordinarily be recovered but escapes as vapor into the atmosphere. Third, the available water resources are of a given size and cannot be increased. For example, the total supply of water of a suitable quality is the same from year to year on an average basis (diminishing in some cases), whereas other materials such as fertilizer, pesticide, etc. can be made available in quantities as needed. *Finally*, the use of water by plants is to a considerable extent uncontrollable by present technology and largely determined by physical and environmental factors.

The physico-chemical properties of water have shaped many of the processes in plants and, indeed, in all organisms. Some of the properties along with typical selected values are cited in Table 6.1.

6.3 The Hydrologic Cycle

6.3.1 Concept and Definition

The word "*hydro*" means water. The hydrologic cycle is also termed as "water cycle." Earth's water is always in movement, and the water cycle or hydrologic cycle describes the continuous movement of water on, above, and below the surface

Table 6.1 Some physico-chemical properties of water

Properties	Values and units
Density at 4°C	1,000 kg m^{-3}
Density at 20°C	998.2 kg m^{-3}
Viscosity at 20°C	0.0010 Pa
Surface tension at 20°C	0.073 N m^{-1}
Diffusion coefficient of small solutes in water	1×10^{-1} m^2 s^{-1}
Molar volume (pure water at 20°C)	1.81×10^{-5} m^3 mol^{-1}
Latent heat of evaporation at 20°C	2.5 MJ kg^{-1}
Latent heat of melting	0.34 MJ kg^{-1}
Saturated vapour pressure of pure water	2.34 kPa at 20°C 4.24 kPa at 30°C

of the earth. Since the water cycle is truly a "cycle," there is no beginning or end. Water can change states among liquid, vapor, and ice at various places in the water cycle, with these processes happening in the blink of an eye and over millions of years. Although the balance of water on earth remains fairly constant over time, individual water molecules can come and go in a hurry. Oceans, rivers, clouds, and rain, all of which contain water, are in a frequent state of change (surface water evaporates, cloud water precipitates, rainfall infiltrates the ground, etc.). However, the total amount of the earth's water does not change. The circulation and conservation of earth's water is called the "hydrologic cycle".

6.3.2 Processes Involved in Hydrologic Cycle

The hydrologic cycle can be thought of as a series of reservoirs or storage areas, and a set of processes that cause water to move between those reservoirs. Understanding the processes and reservoirs of the hydrologic cycle is fundamental to dealing with many issues, including pollution and global climate change. The largest reservoirs are the oceans, which hold about 97% of the earth's water.

Many processes work together to keep earth's water moving in a cycle. There are several processes at work in the hydrologic cycle: evaporation, condensation, precipitation, infiltration, evapotranspiration, surface runoff, stream flow, deep percolation, seepage, spring flow. These occur simultaneously and, except for precipitation, continuously.

For convenience of description, the hydrologic cycle may be deemed to begin with the evaporation of water from the surface of the ocean. The driving force for the hydrologic cycle is the sun, which provides the energy for evaporation. Its energy comes in the form of light, and heat causes water to evaporate from oceans, rivers, lakes, and even soils. "Evaporate" means it turns the water from a liquid state to a gaseous state, or “vapor” state. Warm air currents rising from the earth’s surface lift this water vapor up into the atmosphere. As moist air is lifted, it cools and water vapor condenses to form clouds. Moisture is transported around the globe

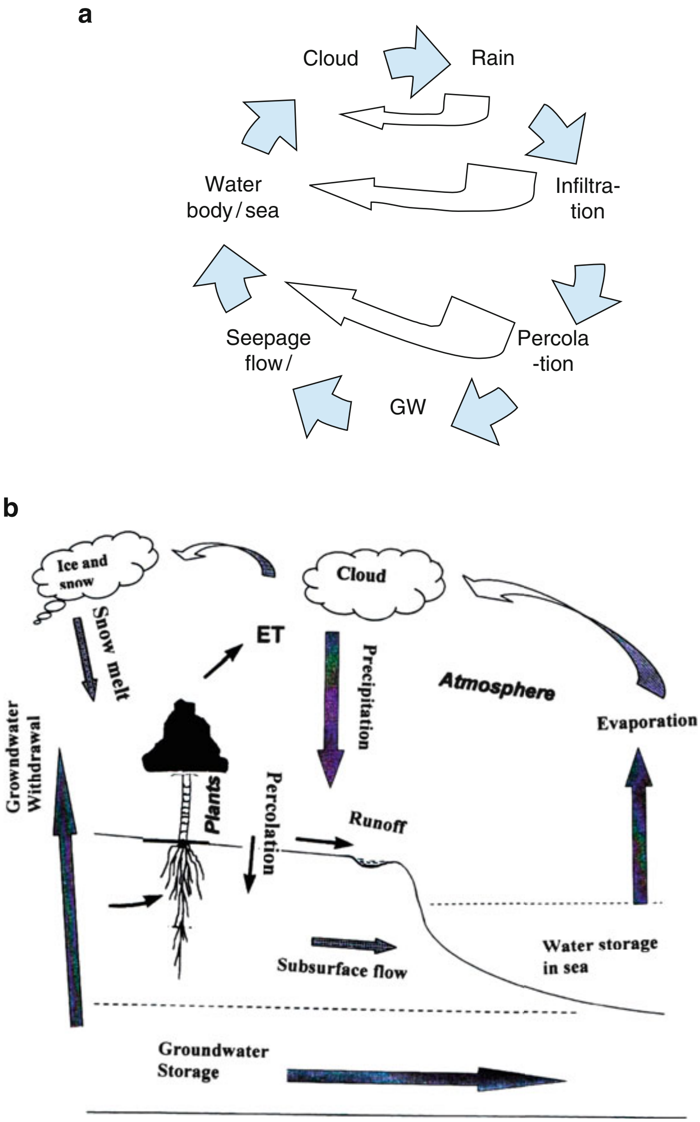

Fig. 6.1 (**a**) Schematic of hydrologic cycle, (**b**) Schematic of processes involved in hydrologic cycle

until it returns to the surface as precipitation. Once the precipitation reaches the earth, one of the following pathways it may follow (Fig. 6.1a, b): (1) Since oceans cover around 70% of the earth's surface, most precipitation falls back into the ocean and cycle begins again. (2) A portion of precipitation falls on land, some of which may evaporate back into the atmosphere; some may soak into the soil and may evaporate directly from the soil surface as it dries or be transpired by growing plants. Water that soaks into the soil can also continue to percolate down through the soil profile into groundwater reservoirs, called aquifers. (3) Groundwater either seeps its way to into the oceans, rivers, and streams, or is released back into the atmosphere through transpiration. (4) Water that does not soak into the soil and moves across the surface as run-off, eventually flows into lakes, streams, and rivers and ultimately to the ocean, where the cycle begins again. (5) Precipitation that falls as snow in glacial regions takes a somewhat different journey, accumulating at the head of glaciers and causing the glaciers to move slowly down the valleys. (6) Water is diverted temporarily from one part of the cycle by pumping it from the ground or drawing it from a river or lake. It is used for a variety of activities such as households, business, and industries; for transporting wastes through sewers; for irrigation of farms and parklands; and for the production of electric power. After use, water is returned to another part of the cycle, discharged downstream, or allowed to soak into the ground.

The water may take any one or a combination of the pathways in its continuous cycle of falling as rainfall or snowfall and returning to the atmosphere. The cycle may be short, or it may take millions of years. It may be captured for millions of years in polar ice caps. The hydrologic cycle is a continuous process by which water is purified by evaporation and transported from the earth's surface (including the oceans) to the atmosphere and back to the land and oceans. All of the physical, chemical, and biological processes involving water as it travels in various paths in the atmosphere, over and beneath the earth's surface and through growing plants, are of interest.

The hydrologists study the fundamental transport processes to be able to describe the quantity and quality of water as it moves through the cycle. The water-resource engineers are concerned of planning, analysis, design, construction, and operation for the control, utilization, and management of water resources.

6.3.3 Impact of Hydrologic Cycle

The properties of water and the hydrologic cycle are largely responsible for the circulation patterns in the atmosphere and the oceans on the earth. Atmospheric and oceanic circulations are two of the main factors that determine the distribution of climatic zones over the earth. Changes in the cycle or circulation can result in major climatic shifts. Additionally, the acceleration of the hydrologic cycle (higher temperature means more evaporation and thus more precipitation) may result in more severe weather and extreme conditions.

6.4 Water Quality Assessment

6.4.1 Meaning of Water Quality

The term “quality,” as applied to water, indicates its physical, chemical, and biological characteristics. The “characteristics” influence the suitability of water for an intended use. To irrigate in a sustainable manner, it is essential to know the quality of the water. Even water of reasonable quality may negatively affect the soil if salinity levels concentrate over time. When considering whether or not to incorporate irrigation as farming practice, it is important to assess the water quality characteristics, land suitability, and crop limitations.

6.4.2 Factors Affecting Quality of Water

Water quality depends on the local geology and ecosystem, as well as human use. Among the human uses, the most significant sources affecting quality of water are as follows:

- Sewage dispersion
- Industrial pollution (chemicals, salts, and metals)
- Pollution from agricultural fields (use of agrochemicals, pesticides, herbicides, etc.)
- Disposal from poultry farms
- Use of water bodies as heat sinks
- Over-use (lowering the water table)

Among the geological factors, the prominent elements are the following:

- Type and characteristics of the rock from which the water bearing formation (stratum) is created
- The soil with which the water has been in contact
- Salinity of the ground water
- Depth to water table from the surface
- Type and quality of the water transmission zone

Water can be of poor quality for irrigation because of the amount of impurity (e.g., salt) it contains or the kinds of impurities present. The most common reasons of irrigation water problem are presence of salts (sodium, chloride) and toxic elements (boron, nitrogen, bicarbonate, iron).

Groundwater quality varies with depth. The deep tube-wells that draw water from 200 m or below contain a very negligible percentage of arsenic. Water quality is highly variable over time because of both natural and human factors. Water temperature, photosynthetic activity, and flows vary with season. Flows, and therefore suspended sediment, can vary daily with rainfall. Nutrient loads can vary with season (home owners fertilize in the spring, farmers fertilize fields at crop grown period), flow (runoff mechanisms affect pollutant washoff), and human management (nitrogen is released after an application). A comprehensive characterization of natural water quality therefore requires a large amount of data.

6.4.3 Factors Affecting Suitability of Water for Irrigation

Suitability of water for irrigation can be described mathematically as:

$$S_{\mathrm{water}} = f(W_{\mathrm{s}}, T_{\mathrm{s}}, S_{\mathrm{t}}, S_{\mathrm{s}}, T, C, WT, D, G_{\mathrm{s}}, M_{\mathrm{c}}, \ldots), \tag{6.1}$$

where S_{water} is the suitability of water for irrigation, f is the function, W_{s} is the salinity of irrigation water, T_{s} is the type or kind of the salt present in water, S_{t} is the soil type, S_{s} is the salinity of soil, T is the salt-tolerant characteristic of the plant to be grown, C is the climate, WT is the depth to water table, D is the drainage facility, G_{s} is the salinity of the ground water, and M_{c} refers to the management practices adopted.

Other factors such as hard pan of clay, lime, etc. can affect the suitability of irrigation water indirectly.

6.4.4 Water Quality Indicators/Parameters and Their Description

Water quality of a stream can be assessed through physical, chemical, and biological attributes. Physical attributes include its pathway, elevation and catchment area, forest canopy (if any), turbidity, temperature, width, depth, velocity, rock size, etc. The most basic physical attribute of a stream is the path along which it flows. Measurements of a stream's physical attributes can serve as indicators of some forms of pollution. Biological attributes refer to the number and types of organisms that inhabit a waterway. Chemical attributes of a waterway can be important indicators of its water quality. These include color, smell, taste, and toxicity of water, indicating whether or not it is safe to use. Chemical quality of water is important to the health of humans as well as the plants and animals that live in and around the stream. For this reason, it is necessary to assess the chemical attributes of water, although it is good by physical assessment.

Understanding the basic chemistry of water quality parameters is an essential first step in making good measurements. Then, the technical measures of water quality - that is, the values obtained when making water quality measurements - are always subject to interpretation from multiple perspectives.

Water quality is a complex issue. Numerous measurements/analyses are involved in water and wastewater quality indicators. These measurements include from simple and basic to more complex types:

- Color of water
- Taste
- Temperature
- Turbidity
- Electrical conductivity
- pH
- Dissolved oxygen (DO)
- Total suspended solids (TSS)
- Total dissolved solids (TDS)
- Biological oxygen demand (BOD)
- Chemical oxygen demand (COD)
- Microorganisms such as fecal coliform bacteria, cryptosporidium
- Nutrients such as phosphorus, nitrogen
- Some toxic elements such as sodium, boron, nitrate, chloride, iron
- Dissolved heavy metals and metalloids (lead, mercury, arsenic, etc.)
- Dissolved organic carbon (DOC)
- Pesticides, herbicides, fungicides
- Radioactive elements

Other composite indices or parameters (especially useful for irrigation water) are as follows:

- Sodium absorption ratio (SAR)
- Residual sodium carbonate (RSC)
- Total hardness (TH)
- Total alkalinity
- Kely's ratio (KR)
- Salt index (SI)

Of the above elements and parameters, the two most common and important measures are the amount of dissolved salts in water and amount of sodium. Total dissolved salt is commonly estimated by electrical conductivity (how well the water conducts electricity). The sodium hazard is commonly estimated by SAR index (describing the amount of sodium in the water compared with the amount of calcium plus magnesium). The above indicators are described below in detail.

6.4.4.1 Color

All drinking and household water should be free from materials related to municipal, industrial, or other discharges, which produce turbidity, color, odor, or other objectionable conditions that interfere with legitimate water uses.

6.4.4.2 Temperature

Water temperature varies with season, elevation, geographic location, and climatic conditions; and is influenced by stream flow, streamside vegetation, groundwater inputs, and water effluent from industrial activities. Water temperature rises when streamside vegetation is removed. Water temperature also increases when warm water is discharged into streams from industries.

6.4.4.3 Electrical Conductivity

Electrical conductivity (EC) is the universal standard measure of water salinity used world wide. Electrical conductivity is the ability of a substance to conduct electricity (reciprocal of resistivity). It is used for the measurement of the salt content of water samples. The conductivity of water is a more-or-less linear function of the concentration of dissolved ions. Additionally, EC value is influenced by the valance of the ions in solution, their mobility, and relative numbers. The temperature also has an important effect: EC increases with the increase in temperature. Conductivity is measured in terms of conductivity per unit length. The SI unit is dS/m (deci-Siemens per meter). It is also measured in mS/m (milli-Siemens /m), or μS/cm (micro-Ssiemens/cm).

Conductivity itself is not a human or aquatic health concern, but because it is easily measured, it can serve as an indicator of other water quality problems. If the conductivity of a stream suddenly increases, it indicates that there is a source of dissolved ions in the vicinity. Therefore, conductivity measurements can be used as a quick way to locate potential water quality problems.

6.4.4.4 pH

pH is a measure of the amount of free hydrogen ions in water. As a definition, pH is the negative logarithm of the molar concentration of hydrogen ions. It represents the acidity or alkalinity of water. A pH of 7 is considered to be neutral. Acidity increases as pH value decreases, and alkalinity increases as pH value increases. More detailed technical description regarding pH is given in Chap. 4 (Soil), Sect. 4.3. The main use of pH in a water analysis is for detecting abnormal water. In water supply, pH is important for coagulation, water softening, and corrosion control.

Most natural waters are buffered by a carbon-dioxide - bicarbonate system, since the carbon dioxide in the atmosphere serves as a source of carbonic acid.

$$\mathrm{H_2CO_2} \rightarrow \mathrm{HCO_3} + \mathrm{H^+} \qquad \mathrm{pH} \sim 7.5$$

This reaction tends to keep the pH of most waters around 7–7.5, unless large amounts of acid or base are added to the water. The pH of water affects the solubility of many toxic and nutritive chemicals; therefore, the availability of these substances to aquatic organisms is affected. As acidity increases, most metals become more water soluble and more toxic. Toxicity of cyanides and sulfides also increases with a decrease in pH (increase in acidity). Ammonia, however, becomes more toxic with only a slight increase in pH.

Most streams draining coniferous woodlands tend to be slightly acidic (6.8–6.5) due to organic acids produced by the decaying of organic matter. In some areas, natural water may also receive acidity from the soils. In waters with high algal concentrations, pH varies diurnally, reaching values as high as 10 during the day when algae are using carbon dioxide in photosynthesis. The pH drops during the night when the algae respire and produce carbon dioxide.

Alkalinity is the capacity to neutralize acids, and the alkalinity of natural water is derived principally from the salts of weak acids. Hydroxides, carbonates, and bicarbonates are the dominant source of natural alkalinity. Reactions of carbon dioxide with calcium or magnesium carbonate in the soil create considerable amounts of bicarbonates in the soil. Organic acids such as humic acid also form salts that increase alkalinity. Alkalinity itself has little public health significance, although highly alkaline waters are unpalatable and can cause gastrointestinal discomfort.

6.4.4.5 Dissolved Oxygen

It refers to the amount of oxygen that is present in a given quantity of water. Dissolved oxygen (DO) is measured as a concentration using unit of milligrams per liter of water (mg/l) or parts per million (ppm).

The amount of DO in streams is dependent on the water temperature, the quantity of sediment in the stream, the amount of oxygen taken out of the system by respiring and decaying organisms, and the amount of oxygen put back into the system by photosynthesizing plants, stream flow, and aeration. The temperature of stream water influences the amount of DO present; less oxygen dissolves in warm water than cold water. For this reason, there is cause for concern for streams with warm water. Oxygen levels in the stream and bay are important because fish and other aquatic animals depend on DO (the oxygen present in water) to live.

6.4.4.6 Turbidity

Turbidity is an indicator of the amount of material suspended in water. It measures the amount of light that is scattered or absorbed. Suspended silt and clay, organic matter, and plankton can contribute to turbidity. Photoelectric turbidimeters measure turbidity in nephelometric turbidity units (NTUs). Turbidity units are supposed to correspond to total suspended solids (TSS) concentrations, but this correlation is only approximate. Turbidity in a stream will fluctuate before, during, and after storm-flow. Turbidity and/or TSS can reduce light penetration, decreasing algal growth, and low algal productivity can reduce the productivity of aquatic invertebrates, a food source of many fish.

Turbidities of less than 10 NTU describe very clear waters. Waters with turbidity in excess of 50 are quite cloudy, and waters with turbidities exceeding 500 are downright muddy. All waters should be free from turbidity, which results in a substantial visual contrast in a water body due to a man-made activity. The upstream appearance of a body of water shall be as observed at a point immediately upstream of a turbidity-causing man-made activity. That upstream appearance should be compared with a point that is located sufficiently downstream from the activity to provide an appropriate mixing zone. For land disturbing activities, proper design, installation, and maintenance of best management practices should be adopted to minimize the turbidity.

6.4.4.7 Total Suspended Solid

Sediment in water is usually measured as a concentration of total suspended solids (TSS), which is the dry weight after filtering a water sample, expressed in mg per liter (mg/l). To determine a suspended sediment load (mass/time), the TSS concentration is multiplied by the flow rate (volume/time). Average TSS concentrations in the range of 25–80 mg/L represent moderate water quality. An average concentration of 25 mg/L is suggested as an indicator of unimpaired stream water quality.

6.4.4.8 Biochemical Oxygen Demand

Natural organic detritus and organic waste from waste water treatment plants, failing septic systems, and agricultural and urban runoff serve as a food source for water-borne bacteria. Bacteria decompose these organic materials using DO, thus reducing the DO. Biochemical oxygen demand (BOD) is a measure of the amount of oxygen that bacteria will consume while decomposing organic matter under aerobic conditions.

BOD is determined by incubating a sealed sample of water for 4–5 days and measuring the loss of oxygen from the beginning to the end of the test. Samples are diluted prior to incubation, otherwise the bacteria will deplete all of the oxygen in the bottle before the test is complete. The main focus of wastewater treatment plants is to reduce the BOD in the effluent discharged in to natural waters. Wastewater treatment plants are designed to function as bacteria farms, where bacteria are fed oxygen and organic waste. The excess bacteria grown in the system are removed as sludge, and this "solid" waste is then disposed of on land.

6.4.4.9 Chemical Oxygen Demand

Chemical oxygen demand (COD) is a measure of the total quantity of oxygen required to oxidize all organic material into carbon dioxide and water. It does not differentiate between biologically available and inert organic matter. The COD values are always greater than BOD values, but COD measurements can be made in a few hours while BOD measurements take 4–5 days.

6.4.4.10 Micro-Organisms

Bacteria and viruses released from human and animal wastes carried to streams can cause disease. Fecal coliform, found in the intestines of warm-blooded animals, is the bacteria for which many states' surface water quality standards are written. Fecal coliform bacteria do not cause disease but are used as an indicator of disease causing pathogens in the aquatic environment. Typical sources of bacteria are sewage from septic system failure and storm-water overflows, poor pasture management and animal-keeping practices, pet waste, and urban runoff. High bacteria levels can limit the uses of water for swimming or contaminate drinking water in groundwater wells. The presence of excessive bacteria also may indicate other problems, such as low DO.

6.4.4.11 Total Dissolved Solids

All natural waters contain some dissolved solids because of the dissolution and weathering of rock and soil. Dissolved solids are determined by evaporating a known volume of water and weighing the residue. Some but not the entire dissolved solids act as conductors and contribute to conductance. Waters with high total dissolved solids (TDS) are unpalatable and potentially unhealthy. TDS for irrigation water should be less than 1,000 ppm.

6.4.4.12 Nutrients Such as Phosphorus, Nitrogen, and Zinc

Phosphorus

Fertilizers, failing septic systems, waste water treatment plant discharges, and wastes from pets and farm animals are typical sources of excess nutrients in surface waters. In aquatic ecosystems, because phosphorous (P) is available in the lowest amount, it is usually the limiting nutrient for plant growth. This means that excessive amounts of phosphorous in a system can lead to an abundant supply of vegetation and cause low DO.

Nitrogen

The forms of nitrogen (N) found in surface water are nitrate, nitrite, and ammonia. Ammonia is usually rapidly converted to nitrate in aerobic waters, as is true in soils (nitrate is a stable form of nitrogen, while ammonia is unstable). Ammonia is associated with municipal treatment discharges.

Zinc

Most commonly, zinc (Zn) enters into the domestic water supply from deterioration of galvanized iron and dezincification of brass. Zinc in water also may result from industrial waste pollution. It is an essential and beneficial element in human growth. Concentrations above 5 mg/l can cause bitter astringent taste and opalescence in alkaline water.

6.4.4.13 Some Toxic Elements

Boron

All natural water contains boron in minute concentration. Though it is essential for healthy plant growth, it becomes toxic if present in soil solution in more than a few parts per million (ppm). Excessive boron can cause leaf burn. Plant species differ in their tolerance to excessive boron concentration. The permissible limit of boron in irrigation water ranged from 0.33 to 1.25 ppm for sensitive crops, 0.67–2.25 ppm for semitolerant crops, and 1.0–3.75 ppm for tolerant crops.

Nitrate

For drinking purpose, nitrate (NO_3) present in excessive amounts is toxic. An increased level of NO_3 has been linked with blue-baby syndrome in infants. No diseases have definitely been proven to be caused by water containing less than 10 mg/l NO_3-N. In 1986, EPA (USA) established a 10 mg/l concentration of NO_3 as a standard for drinking water. For irrigation water, excessive nitrogen can cause reduced grain or seed yield (due to higher vegetative growth and slow rate of assimilate partitioning) and lower sugar content in sugar beat.

Chloride

Excessive accumulation of chloride can cause plant injury, leaf burn, or drying of leaf tissue. In case of sprinkler irrigation, chloride toxicity can occur by direct leaf absorption. Chlorides occur in natural waters in varying concentrations.

The chloride contents normally increase as the mineral content increases. Upland and mountain water are usually quite low in chlorides, whereas rivers and groundwater usually have a considerable amount. Sea and ocean water represent the residues resulting from partial evaporation of natural waters that flow into them and chloride levels are very high.

Chlorides in reasonable concentrations are not harmful to human. At concentrations above 250 mg/l, it causes a salty taste to water, which is objectionable to many people. For public use, chlorides are limited to 250 mg/l.

Iron

Iron can cause soil acidification and unavailability of other nutrients, specially phosphorus and molybdenum. Iron, as well as manganese, creates serious problems in public water supplies. The problems are most critical for groundwater if exists as insoluble ferric oxide or hydroxide and iron sulfide. In some cases, it also occurs as ferrous carbonate, which is very slightly soluble in water. When such water are exposed to the air so that oxygen can enter, oxidation of iron and manganese takes place (to the Fe^{3+} and Mn^{3+} states) and they become turbid. The water then becomes unacceptable from the aesthetic viewpoint. Iron also imparts a test to water, which is detectable at very low concentrations.

6.4.4.14 Dissolved Metals and Metalloids

Arsenic

Arsenic is a metalloids element, meaning that it has both the property of metal and nonmetal. It is carcinogenic and poisonous. Most of the arsenic compounds are water soluble. Arsenic found in water may derive from geological formation, industrial discharge, and arsenical insecticides. Inorganic arsenic is more toxic than organic arsenic.

Lead

Lead sources are batteries, gasoline, paints, caulking, rubber, and plastics. Lead can cause a variety of neurological disorders. In children, it inhibits brain cell development. Approximately 20% of human exposure to lead is attributable to lead in drinking water.

Cadmium

Cadmium is toxic to both humans and fish and seems to be a cumulative toxicant. Cadmium replaces zinc in the body, and long-term consumption of cadmium may lead to bodily disorders.

Copper

Metal plating, electrical equipment, pesticides, paint additives, and wood preservatives are sources of copper.

Other toxicants that are associated with industrial effluent are mercury and silver.

6.4.4.15 Radioactive Elements

Radon is a naturally-occurring radioactive gas that may cause cancer, and may be found in drinking water and indoor air. Other sources of radioactive elements may be nuclear waste from nuclear plant.

6.4.4.16 Pesticides, Herbicides, and Organics

Herbicides, fungicides, and pesticides can accumulate in aquatic environments and cause toxic effects on aquatic life and increase health risks of drinking water. These chemicals are at very low concentrations in the natural environment, and they are typically introduced to surface waters as waste from human activities.

Pesticides and herbicides are found in streams and rivers draining agricultural and residential areas, usually during periods of extended wet weather or intense precipitation when overland flow is most likely. These substances are toxic to many aquatic organisms, and they may act as mutagens for human beings. Since water treatment plants are not designed to remove these substances, it is important to prevent their introduction to drinking water supplies.

There are a wide variety of organic chemicals, including chlorinated hydrocarbons that are used as solvents, cleaners, lubricants, insulators, and fuels in many industries. Many of these chemicals are believed to be cancer-causing agents. Since these are organic chemicals, most of them are biologically active to some degree. This means that bacteria in the environment often degrade these substances into byproducts. Unfortunately, some of these byproducts are more toxic than the original substance.

The Environmental Protection Agency (EPA) of USA and other countries regulates concentrations of literally hundreds of these chemicals in drinking water and groundwater. These chemicals are often found in association with each other, and the inter-actions of these chemicals as mutagens are poorly understood. Because they are suspected cancer-causing agents, regulatory levels for many of these chemicals are in the parts per billion range, which means that analytical techniques for these chemicals are rigorous, time-consuming, and expensive.

6.4.4.17 Composite Indices

Sodium Absorption Ratio

Sodium absorption ratio (SAR) describes the amount of excess sodium in relation to calcium and magnesium (i.e., comparative concentration of Na^+, Ca^{2+}, and Mg^{2+}). It indicates water's potential to cause sodic conditions and poor soil structure.

SAR is defined by the following equation:

$$SAR = \frac{Na^+}{\frac{\sqrt{(Ca^{++} + Mg^{++}}}{2}}, \tag{6.2}$$

where Na is the sodium in me/l (milli-equivalent per liter), Ca is the calcium in me/l, and Mg is the magnesium in me/l.

Soil solution SAR is closely linked to the SAR of the irrigation water. An adjusted SAR_{adj} value may be calculated for water with high carbonate and bicarbonate content. High carbonate and bicarbonate present in water will cause the precipitation of the calcium and magnesium and increase the relative concentration of sodium, thus increasing the SAR index.

Residual Sodium Carbonate

It is another alternative measure of the sodium content in relation with Ca and Mg. It is expressed as:

$$RSC = (CO_3{}^{--} + HCO_3{}^{-}) - (Ca^{++} + Mg^{++}), \tag{6.3}$$

where CO_3, HCO_3, Ca, and Mg are the carbonate, bi-carbonate, calcium, and magnesium ion concentration in meq/l, respectively. If the $RSC < 1.25$, the water is considered safe. If the $RSC > 2.5$, the water is not appropriate for irrigation.

Kelley's Ratio

Kelley's ratio (KR) is expressed as:

$$KR = \frac{\mathrm{Na}^{+}}{\mathrm{Ca}^{++} + \mathrm{Mg}^{++}}, \tag{6.4}$$

The ionic concentrations are in milli-equivalent per liter (meq/l).

Kelley suggested that this ratio for irrigation water should not exceed unity. The *KR* value within this limit indicates a good tilth condition of the soil with no permeability problem.

Total Hardness

Hard water is the water that has high cation content. The cations include calcium (Ca^{2+}), magnesium (Mg^{2+}), iron (Fe^{2+}), manganese (Mn^{2+}), aluminum, etc. Most of the hardness of water is due to the presence of Ca^{2+} and Mg^{2+}. The total water hardness (TH) is expressed as ppm or mg/l of calcium carbonate in water. Considering calcium and magnesium as the major ions, *TH* is calculated as:

$$\text{or } TH = \mathrm{Ca} \times \frac{\mathrm{CaCO_3}}{\mathrm{Ca}} + \mathrm{Mg} \times \frac{\mathrm{CaCO_3}}{\mathrm{Mg}}, \tag{6.5}$$

where *TH*, Ca, and Mg are expressed in ppm, $\mathrm{CaCO_3}$/Ca is the ratio of equivalent weights of $\mathrm{CaCO_3}$ and Ca, and $\mathrm{CaCO_3}$/Mg is the ratio of equivalent weights of $\mathrm{CaCO_3}$ and Mg.

$$TH = 2.497\mathrm{Ca} + 4.115\mathrm{Mg}, \tag{6.6}$$

where all the items are expressed in ppm.

Water is said to be hard if *TH* is in the range of 140–210 ppm, moderately hard if TH is 210–320 ppm, hard if TH is 320–530 ppm, and very hard if TH>530 ppm.

TDS

For good quality water, *TDS* should be more than 1,000 ppm.

Salt Index

Salt index is expressed as:

$$\mathrm{SI} = \text{Total Na} - 245 - 4.85\ (\text{total Ca} - \text{Ca in } \mathrm{CaCO_3}), \tag{6.7}$$

where all the elements are expressed in ppm.

6.4.5 Water Quality Evaluation: Standards and Guidelines

Water quality standards are the foundation of the water quality-based pollution control program. Water quality standards define the goals for a water-body by designating its uses, setting criteria to protect those uses, and establishing provisions to protect water-bodies from pollution.

Evaluation of water quality depends on its specific use. Experience and experimentation over the years have given rise to a set of guidelines for determining the suitability of water for different purposes. Water quality criteria can never be absolute because soils, management, and drainage can influence water suitability. It is also influenced by social and economic factors.

There are several quality classifications in relation to the use of water:

- Irrigation
- Drinking
- Industrial

The chemical, physical, and biological aspects of water quality are inter-related and must be considered together. For example, higher water temperature reduces the solubility of DO, and may cause a dissolved oxygen shortage that could kill sensitive fish species.

6.4.5.1 Irrigation Water Quality

Guideline for irrigation water quality has been established by the World Food and Agricultural Organization, FAO (FAO Irrigation and Drainage Paper No. 29 Rev.1, Ayers and Westcot 1985). The guidelines are described in Table 6.2. The guideline is based on the assumption that the soils are sandy loam to clay loams, have good drainage, are in arid to semi-arid climates, irrigation is sprinkler or surface, root depths are normal for soil, and that the guidelines are only approximate. Wide deviations from the assumptions of the guideline in a particular situation might result in wrong judgments on the usability of a particular water supply, especially if it is a border line case.

6.4.5.2 Assumptions in the Guideline

The guidelines in Table 6.2 are based on some basic assumptions, intended to cover the wide range of conditions encountered in irrigated agriculture. The values shown are applicable under normal field conditions prevailing in most irrigated areas in the arid and semi-arid regions of the world. If the water is used under greatly different conditions, the guidelines may need to be adjusted. The basic assumptions are as follows:

Table 6.2 Guidelines for interpretation of water quality for irrigation (After Ayers and Westcot 1985; with permission)

Water constituent	Unit	Degree of restriction on use (i.e., intensity of problem)		
		None	Slight to moderate	Severe
Salinity (affects crop water availability)[a]				
EC_w	dS/m	<0.7	0.7–3.0	>3.0
TDS	mg/l or ppm	<450	450–2,000	>2,000
Salinity, infiltration influence				
If *SAR*[b] = 0–3 and EC_w =		>0.7	0.7–0.2	<0.2
= 3–6 =		>1.2	1.2–0.3	<0.3
= 6–12 =		>1.9	1.9–0.5	<0.5
= 12–20 =		>2.9	2.9–1.3	<1.3
= 20–40 =		>5.0	5.0–2.9	<2.9
Specific ion toxicity (affects sensitive crops)				
Sodium (Na)[c]				
Surface irrigation	SAR	<3	3–9	>9
Sprinkler irrigation	me/l[d]	<3	>3	
Chloride (Cl)[c]				
Surface irrigation	SAR	<4	4–10	>10
Sprinkler irrigation	me/l	<3	>3	
Boron (B)	mg/l	<0.7	<0.7–3.0	>3.0
Miscellaneous effects (affects susceptible crops)				
Nitrogen (NO_3-N)[e]	mg/l	<5	5–30	>30
Bicarbonate (HCO_3)	me/l	<1.5	1.5–7.5	>7.5
pH[f]		Normal range 6.5–8.4		

[a] EC_w is the electrical conductivity, a measure of the water salinity, reported in deci-Siemens per meter at 25°C (dS/m) or equivalent units (mhos/cm). TDS means total dissolved solids, in milligrams per liter (mg/l)

[b] *SAR* is the sodium absorption ratio. At a given SAR, infiltration rate increases as water salinity increases

[c] For surface irrigation, most tree crops and woody plants are sensitive to sodium and chloride; use the values shown. Most annual crops are not sensitive; for surface irrigation use the salinity tolerance tables from Ayers and Westcot (1985), p 31. With overhead sprinkler irrigation and low humidity (<30%), Na and Cl may be absorbed through the leaves of sensitive crops

[d] To convert ppm to me/l, divide ppm by the following values for each component: Na−23, Cl−23, HCO_3−61, and B−11

[e] NO_3-N means nitrate nitrogen reported in terms of elemental N. NH_4-N and organic - N should be included when wastewater is being tested

[f] Fertilizer application can change water/ soil pH and have an effect on the potential toxicity of ions in the irrigation water

(a) *Restriction on use/yield potential*. Three divisions of restriction are somewhat arbitrary since change occurs gradually and there is no clear-cut breaking point. “No restrictions on use” means full production capability of all crops without the use of special practices. A restriction on use indicates that there may be a limitation in choice of crops, or special management may be needed to maintain full production capability.

(b) *Site condition*. The soil texture ranges from sandy-loam to clay-loam with good internal drainage, the climate is semi-arid to arid, and rainfall is low. Rainfall does not play a significant role in meeting crop water demand or leaching.

(c) *Methods and timing of irrigation.* Normal surface or sprinkler irrigation methods are used, and the crop uses about 50% stored soil-water before the next irrigation. At least 15% of the applied water percolated below root zone (LF $\geq$15%).

(d) *Water uptake by crops.* On average, about 40% of available water is taken from the upper quarter, 30% from the 2nd, 20% from the 3^{rd}, and 10% from the lowest quarter of the root zone.

Higher salinity in the lower root zone becomes less important if adequate moisture is maintained in the upper, “more active” part of the root zone.

On the basis of the FAO guidelines, many countries *or* states (*or* province) have adopted their own quality standard. The water quality standard of Bangladesh (for irrigation and drinking) is given in Table 6.3.

6.4.5.3 Drinking Water

Drinking water quality varies from place to place, depending on the condition of the source water from which it is drawn and the treatment it receives. Drinking water criteria and standard have been suggested by World Health Organization (WHO), and have been developed by many countries in the world. The WHO Guidelines for drinking-water quality is intended for use as a basis for the development of national standards in the context of local or national environmental, social, economic, and cultural conditions.

Standard for Arsenic

“The International Standards for Drinking Water” was established in 1958 as 0.20 mg/l as an allowable concentration for arsenic. In 1963, the standard was reevaluated and reduced to 0.05 mg/l. In 1984, this was maintained as WHO’s “Guideline value”; and many countries have kept this as the national standard or as an interim target. According to the last edition of the WHO Guidelines (1993) for drinking water quality, inorganic arsenic is a documented human carcinogen. The concentration of 0.01 mg/l was established as a provisional guideline value for arsenic. Because the guideline value is restricted by measurement limitations, and 0.01 mg/l is the realistic limit to measurement, this is termed a provisional guideline value.

In United States of America, the maximum contamination level (MCL) for total arsenic in drinking water was 50 ppb (0.050 mg/l) since 1942. United States Environment Protection Agency (USEPA) had revised the arsenic MCL from 50 to 20 ppb in 1994, and in 2001 the USEPA set the new arsenic standard for drinking water at 10 ppb (USEPA 2001).

On the basis of health criteria, the guideline value for arsenic in drinking-water would be less than 0.01 mg/l.

Table 6.3 Water quality standard of Bangladesh (GOB 1997)

Chemical/mineral	Drinking limit (ppm)[a]	Irrigation limit (ppm)[a]
Aluminium (Al)	0.2	1.0
Amomonia (NH_3)	0.5	3.0
Arsenic (As)	0.05	0.2
Bicarnate (HCO_3)	–	200 (2.5 me/l)
Biochemical oxygen demand (BOD)	0.2	10 or below
Boron (B)	1.0	2
Cadmium (Cd)	0.005	0.1
Calcium (Ca)	75	NYS
Chemical oxygen demand (COD)	4	NYS
Chloride (Cl)	150–600	600
Coliform (fecal)	0 n/100 ml	10 n/100 ml
Coliform (total)	0 n/100 ml	1,000 ppm or below
Copper (Cu)	1	3
Dissolved oxygen (DO)	6	4.5–8
Electrical conductivity (EC)	600–1,000 µS/cm	1,200 µS/cm
pH (hydrogen ion concentration)	6.5–8.5	6.0–8.5
Iron (Fe)	0.3–1.0	1–2
Lead (Pb)	0.05	0.1
Magnesium (Mg)	30–50	NYS
Manganese (Mn)	0.1	5
Mercury (Hg)	0.001	0.01
Nickel (Ni)	0.1	0.5
Nitrate (NO_3)	10	10 ppm as N_2
Nitrite (NO_2)	<1	NYS
Phosphate (PO_4)	6	10
Phosphorus (P)	0	15
Potassium (K)	12	NYS
Selenium (Se)	0.01	0.05
Silver (Ag)b	0.02	NYS
Sodium (Na)	200	NYS
Sodium absorption ratio (SAR)	–	23
Sulfate (SO_4)	400	1,000
Suspended solids (SS)	10	NYS
Total alkalinity	–	–
Total hardness	200–500 mg/l	–
Temperature	20–30°C	20–30°C
Tin (Sn)	2	NYS
Total dissolved solid (TDS)	1,000	2,100
Zinc (Zn)	5	10

[a] Unit is ppm unless otherwise stated

NYS, not yet standardized

6.4.6 Classification of Water for Its Quality Based on Different Parameters

Different researchers have classified water based on certain parameters or indicators, and for certain purposes. Water of marginal or undesirable quality may be used successfully when the undesirable aspects of the water are off-set by certain desirable aspects of the water or positive conditions of its use. On the other hand, water of good quality having low salt or undesirable element can accumulate over time, and the soil may become unsuitable for crop production. Water that is unsuitable for a particular crop (e.g., sensitive crops such as beans) and soil (such as heavy clay) may be suitable for another crop (salt tolerant crops such as cotton, wheat) and soil (such as sandy or drainable soil). Thus, it is difficult to classify the water in a straight forward way for all conditions. The literature also suggests that for a particular salinity level, the effect of water containing a single salt is different from that of the multiple salts.

In most classification systems, it is assumed average conditions of soil texture, climate, quantity of irrigation water used, infiltration rate, drainage, and salt tolerance of crops. Deviations of one or more factors from the assumed conditions may make it unsafe to use water according to the prescribed class.

Richards (1954) classified irrigation water based on electrical conductivity (EC) and sodium absorption ratio (SAR), and the classification was shown in Fig. 6.2. Consideration should also be given to the other independent elements such as chloride, iron, boron, bicarbonate, or other toxic elements, which may change the quality rating. While recommending water having particular quality, drainage and other management practices should also be taken into account.

Considering salinity and sodium hazard, bicarbonate, iron, and other minor but toxic elements with respect to soil, plant, and possible human intake through food chain, the irrigation water can be classified as follows (Table 6.4).

6.5 Water Analysis: Measuring the Quality of Water

6.5.1 Analytical Methods

Water quality for intended use can be evaluated with a water quality test. An analytical method is a procedure used to analyze a sample to determine the identity and concentration of a specific sample component. Many government agencies, universities, and consensus methods organizations develop analytical methods.

Certain parameters, which vary greatly with time and space, can be measured in situ. Such examples are as follows:

Temperature: Using a mercury thermometer
pH: Using pH meter (different models are available), pH indicating litmus paper

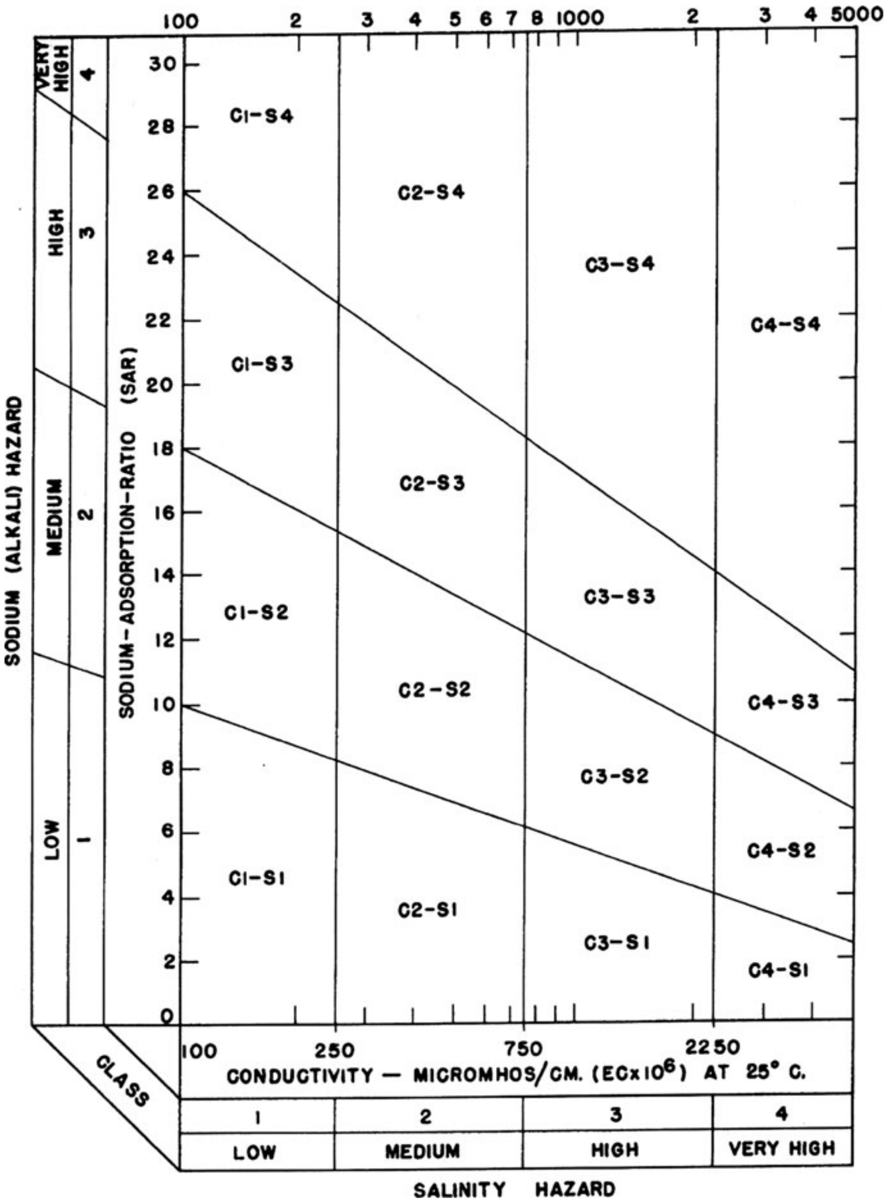

Fig. 6.2 Diagram for the classification of irrigation water (after Richards 1954)

Electrical Conductivity: With a conductivity meter (handy types are available in the market)

Arsenic: Arsenic test kitbox

Moreover, various mineral contents in water (sodium, potassium, calcium, magnesium, iron, zinc, copper, chromium, lead, arsenic) can be determined by

Table 6.4 Water quality class for irrigation based on sodium, salinity, and toxicity effect[a]

Water quality class	Range of parameters/elements								
	pH	*EC*(dS/m)	SAR	As(ppm)	Cl(meq/l)	B(ppm)	HCO_3(meq/l)	Pb (ppm)	Fe(ppm)
Excellent	6.8–7.2	<0.2	<2.0	Nill	<2.0	<0.5	<1.0	Nill	<1.0
Good	6.5–7.5	0.2–0.5	2–3	<0.001	2–3	0.5–0.7	1.0–1.5	0–0.05	1.0–2.0
Moderate	6.2–7.8	0.5–1.0	3–6	0.001–0.05	3–6	0.7–2.0	1.5–5.0	0.05–1.0	2.0–4.0
Bad	6.0–6.2, 7.8–8.0	1.0–3.0	6–9	0.05–0.01	6–9	2–3	5.0–8.0	1.0–3.0	4.0–5.0
Very bad	<6.0, >8.0	>3.0	>9	>0.01	>9	>3	>8.0	>3.0	>5.0

[a] Assuming average condition of climate, soil, drainage, crop tolerancy, management, human tolerancy, and surface irrigation system

atomic absorption spectrophotometer (AAS). It is beyond the scope of this book to go into detailed methodologies of water and waste-water analysis. Some rigorous references in this area are cited below:

- Standard Methods for Examination of Water & Wastewater (Rand et al. 1976 and later editions, APHA Pub.)
- FAO Soils Bulletin 10 (Dewis and Freitas 1970)
- FAO Soils Bulletin 31 (Rhoades and Merrill 1976)
- USDA Handbook 60 (Richards 1954)

6.5.2 Some-Related Terminologies and Relationships

6.5.2.1 Milliequivalent Per Liter

It is the concentration of a solution having one milliequivalent of an ion or compound in one liter solution. Milliequivalent per liter,

$$\text{Meq/l} = (\text{concentration of salt in mg/l})/\text{equivalent weight}$$

6.5.2.2 Molar Solution

It is solution having salt concentration of 1 g molecular weight dissolved in 1 l (water solution).

Equivalent wt = atomic wt/valency
Milliequivalent wt = equivalent wt/1,000
Equivalent per million, epm = (concentration of salt in ppm)/equivalent weight
mg/l ≈ ppm, meq/l = epm (equivalent per million)
mg/l = 0.64 × EC (in μmhos/cm)

Table 6.5 Atomic wt. and equivalent wt of different elements and compounds

Element	Atomic wt	Equivalent wt
Na^+	23	23
K^+	39.1	39.1
Ca^{++}	40	20
Mg^{++}	24.3	12.16
Fe^{+++}	56	18.66
As^{++}	74.92	37.46
Cl^-	35.46	35.46
NO_3^-	52	52
CO_3^{--}	60	30
SO_4^{--}	96	48
HCO_3^-	61	61

Note. $^+$cation, $^-$anion

= 640 × EC (in dS/m), for waters and soil extracts having conductivity up to 5 dS/m.

Atomic weight and equivalent weight of different elements and compounds are given in Table 6.5.

6.5.3 Workout Problems on Assessing Water Quality

Example 6.1. A water sample has the following chemical composition (mg/l, if otherwise not stated):

$EC = 6.0$ dS/m, $Ca^{2+} = 60$, $Mg^{2+} = 30$, $K^+ = 26$, $Na^+ = 42$, $Fe^{3+} = 0.8$, $SO_4^{2-} = 10$, $NO_3^- = 12$, $As = 0.015$, $B = 2.5$.

- Classify the water quality for irrigation on the basis of EC, SAR.
- Comment on the standard of the water for irrigation based on Boron and Arsenic.
- Comment on the standard of the water for human drinking based on Arsenic and nitrate concentration.

Solution

1. We know, $SAR = \frac{Na^+}{\sqrt{\frac{(Ca^{++}+Mg^{++}}{2}}}$,

where all the ions are expressed in meq/liter.

Anion/cation	mg/l	eq.wt.	meq/l
Ca^{++}	60	20	3
Mg^{++}	30	12.16	2.47
K^+	26	39.1	0.66
Na^+	42	23	1.83

Putting the values in above equation, $SAR = 1.56$ (which is <10)

Given, $EC = 6.0$ dS/m (which is between 2.5 and 7.5)

Considering the classification system of Richards (1954):

With respect to sodium or alkali hazard, i.e. SAR value, the water is "Low sodium water."

With respect to salinity hazard, i.e. EC value, the water is "Medium saline water"

2. Given: B = 2.5 mg/l, As = 0.015 mg/l

Considering B concentration, the water is moderately restricted for irrigation as it is >1.0 mg/l, permissible limit.

Considering As concentration, the water is suitable for irrigation as As < 0.1 mg/l, permissible limit, according to FAO guideline.

3. Given: $NO_3 = 12$ mg/l, As = 0.015 mg/l

Considering NO_3 concentration, the water is not suitable for drinking as it is >10 mg/l, permissible limit.

Considering As concentration, the water is not suitable for drinking as it is >0.01 mg/l, the permissible limit suggested by WHO.

Example 6.2. A water sample from DTW outlet was analyzed and the following chemical composition was found (mg/l, if otherwise not stated):

$EC = 3.5$ dS/m, $Ca^{2+} = 80$, $Mg^{2+} = 22$, $K^{+} = 16$, $Na^{+} = 32$, $Fe^{3+} = 1.2$, $CO_3^{2-} = 27$, $SO_4^{2-} = 28$, $NO_3^{-} = 10$, $HCO_3^{-} = 225$, $Cl^{-} = 65$, $As = 0.15$.

1. Classify the water quality for irrigation on the basis of EC, SAR, RSC and HT (total hardness).
2. Comment on permeability effect based on EC and SAR.
3. Comment on the standard of the water for human drinking based on Arsenic and nitrate concentration.

Solution

1. We know, $SAR = \frac{Na^{+}}{\frac{\sqrt{(Ca^{++}+Mg^{++}}}{2}}$,

where all the ions are expressed in meq/liter.

Cation	mg/l	equ.wt.	meq/l
Ca^{++}	80	20	4
Mg^{++}	22	12.16	1.81
Na^{+}	32	23	1.39
HCO_3^{-}	225	61	3.69
CO_3^{-}	27	30	0.90

Putting the values of Na, Ca, and Mg, $SAR = 1.15$
We know,

$$RSC = (CO_3^{--} + HCO_3^{-}) - (Ca^{++} + Mg^{++}),$$

where the ion concentration in meq/l, respectively.
Putting the values, $RSC = -1.22 = 0$ (as negative) ppm
We know, $TH = 2.497\ Ca + 4.115\ Mg$, Where all the items are expressed in ppm.
Putting the values of Ca and Mg, $TH = 290.29$ ppm
With respect to salinity hazard, i.e., EC value 3.5 dS/m), the water is "Medium saline water"
With respect to SAR value (1.15), the water is "Low sodium water."
With respect to RSC value (0), the water is "safe."
With respect to water hardness ($HT = 290.29$), the water is "moderately hard."

2. At given EC (3.5 dS/m) and SAR (1.15) value, the irrigation water is safe for present irrigation use. But the EC and SAR of the top soil should be monitored over time, so that the top soil EC and SAR must not exceed critical or permissible limit. Otherwise, permeability and crusting hazards may occur.

3. Given, As = 0.15 mg/l, which is >0.01 mg/l, WHO permissible limit; thus the water is *unsuitable* for drinking with respect to Arsenic level.

NO_3 = 10 mg/l, which is equal to maximum permissible limit; thus the water is *marginally acceptable* for drinking.

6.5.4 Checking the Correctness of Water Analysis

6.5.4.1 Checking Methods

The following procedures are applicable for checking the correctness of water analysis:

- Anion-cation balance
- Measured vs. calculated TDS balance
- Measured vs. calculated EC balance
- Calculated or measured TDS to EC ratio

Anion-Cation Balance

The sum of anions and cations, when expressed as meq.l^{-1}, must be balanced, because all portable waters are electrically neutral.

The test is based on the percentage difference as follows:

$\%\ \text{Difference} = (\Sigma\text{Cations} - \Sigma\text{Anions}) \times 100/(\Sigma\text{Cations} + \Sigma\text{Anions})$

The acceptable difference is from 5 to 10%. The range between 2 and 5% is desirable.

Measured and Calculated TDS Balance

Ideally, measured TDS ≈ calculated TDS.

Total dissolved solid (TDS) is calculated from the sum of major ionic constituents, expressed as mg/l.

$$TDS = CO_3^{--} + HCO_3^{-} + Ca^{++} + Mg^{++} + Na^{+} + K^{+} + SO4^{--} + NO_3^{-} + Cl^{-} + F.$$

If the measured *TDS* is higher than the calculated one, a significant contributor may not be included in water analysis. On the other hand, if the measured TDS is less than the calculated one, the higher ion sum is suspected. The water sample should be subject to reanalysis. The acceptable ratio of the measured and calculated TDS is 1.0–1.2, i.e.

$1.0 < (\text{measured TDS}/\text{calculated TDS}) < 1.2$

Measured and Calculated EC Balance

Ideally, measured EC ≈ calculated EC.

Calculated EC is obtained by considering sums of anion or cation, expressed as meq.l^{-1}, i.e. EC = $\sum$anion or $\sum$cation.

Measured value of EC is obtained from instrumental reading, inserted into the targeted water sample. if the calculated EC is higher than the measured EC value, the higher ion sum is suspected. On the other hand, if the calculated EC is lower than the measured EC value, the water sample should be reanalyzed. The acceptable criterion of the deviation is:

$0.9 < (\text{Calculated EC}/\text{measured EC}) < 1.0$

Calculated or Measured TDS to EC Ratio

The acceptable value of the ratio of calculated or measured TDS to EC is from 0.55 to 0.70. That is,

$0.55 < \text{TDS}/\text{EC} < 0.70$

If the ratio falls below 0.55, the lower ion sum is suspected, and the water sample should be reanalyzed. If the reanalysis causes no changes, some unmeasured constituents such as nitrate, ammonium, etc. may be present in a significant amount. If the ratio is above 0.7, the higher ion sum is suspected.

6.5.4.2 Workout Problems on Checking Correctness of Water Analysis

Example 6.3. A canal water has the following chemical composition (meq/l):

$$\mathrm{Ca} = 2.0, \mathrm{Mg} = 4, \mathrm{K} = 0.5, \mathrm{Na} = 10, \mathrm{HCO_3}^- = 0.0, \mathrm{CO_3}^- = 0.8, \mathrm{SO_4}^- = 0.0, \mathrm{Cl}^- = 2.0, \mathrm{NO_3}^- = 0.05, \mathrm{Fe}^{+++} = 0.1$$

Check the anion-cation balance of the sample, and comment on it

Solution

Sum of cations = (Ca + Mg + K + Na + Fe) = 8.6
Sum of anions = (HCO_3 + CO_3 + SO_4 + Cl + NO_3) = 2.85
% Difference = (ΣCations − ΣAnions)×100/(ΣCations + ΣAnions)
=50.22, which is much greater than the allowable limit (10%)
So, the sample should be reanalyzed.

Example 6.4. A canal water sample has the following composition (mg/l):

$$\mathrm{Ca}^{++} = 90, \mathrm{Mg}^{++} = 30, \mathrm{K}^+ = 10, \mathrm{Na}^+ = 40, \mathrm{HCO_3}^- = 31, \mathrm{CO_3}^- = 12, \mathrm{SO_4}^{---} = 2, \mathrm{Cl}^- = 95, \mathrm{NO_3}^- = 2, \mathrm{TDS} = 600$$

1. Check the anion-cation balance.
2. Check whether the measured and calculated TDS is within acceptable limit.

Solution

1.

Anion/cation	Con. (mg/l)	equ.wt.	Con. (meq/l)
Ca^{++}	90	20	4.5
Mg^{++}	30	12.16	2.5
K^{+}	56	39.1	1.4
Na^{+}	40	23	1.7
Total			10.1
$HCO3^{-}$	131	61	2.1
$CO3^{-}$	12	30	0.4
$SO4^{--}$	2	48	0.0
Cl^{-}	95	35.46	2.7
$NO3^{-}$	2	52	0.0
$Fe3^{+}$	68	18.66	3.6
Total			9.0

Sum of cations = 10.1
Sum of anions = 9.0
% Difference = $(\Sigma\text{Cations} - \Sigma\text{Anions})\times 100/(\Sigma\text{Cations} + \Sigma\text{Anions})$
$= (10.1 - 9.0) \times /(10.1 + 9.0)$
= 6.2, which is less than 10
Thus, the analysis seems OK. (*Ans*)

2. Given measured *TDS* = 600

Calculated TDS = sum of cations + sum of anions = 526
Ratio of measured to calculated *TDS* = 600/526 = 1.1, which is less than 1.2
Thus, the measured and calculated TDS are within acceptable limit. (*Ans*)

6.6 Problems with Marginal/Poor Quality Irrigation Water for Crop Production

6.6.1 Major Issues and Considerations

The importance of irrigation in the world's agriculture is rapidly increasing. Although it is practiced on a large scale mainly in arid and semi-arid zones, supplementary irrigation has become popular in semi-humid regions as well. The impact of irrigation speaks for itself in terms of increased crop production. However, the question remains as to how sustainable the achievement may be. Supplies of good quality irrigation water are expected to decrease in the future because the development of new water supplies will not keep pace with the increasing water needs of industries and municipalities. Thus, irrigated agriculture faces the challenge of using less water, in many cases of poorer quality, to provide food and fiber for an expanding population.

In many cases, it may be necessary to make increased use of municipal wastewater and irrigation drainage water. Aside from increased levels of nitrogen, phosphorous, and potassium; the salinity (total salt content) and sodicity (sodium content) of these waters will be higher than that of the original source water because of the direct addition of salts to the water and the evapotranspiration that occurs as water is used. Although the use of these waters may require only minor modifications of existing irrigation and agronomic strategies in most cases, there will be some situations that will require major changes in the crops grown, the method of water application, and the use of soil amendments.

6.6.2 Impact on Soil Physical Properties

Infiltration rates are particularly sensitive to sodium absorption ration (SAR) and salinity. When a soil is irrigated with high sodium water, sodium is accumulated at the surface soil, which weakens soil structure. The soil aggregates of the surface soil are then dispersed in to smaller particles, and clog soil pores. This causes infiltration problem. The problem may also be caused by extremely low calcium content of the soil surface.

6.6.3 Problem of Toxicity

Toxicity problem may occur if certain elements (ions) present in water are taken up by the plant and accumulated to concentrations high enough to cause damage of crop or reduced yield. The degree or severity of damage, of course, depends on the crop sensitivity, the amount of uptake, duration of exposure, volume of water transpired by the plant, and concentration of the toxic ion. The absorbed ions are transported to the leaves, where they accumulate during transpiration. Toxicity can also occur from direct absorption of the toxic ions by leafs or fruits in case of sprinkler irrigation. The major ions that may cause such a problem are boron, chloride, sodium, bicarbonate, etc.

6.6.4 Other Miscellaneous Problems

Suspended organic and inorganic sediments can cause problem in irrigation system through clogging of gates, sprinkler heads, and drippers. Sediments may reduce water infiltration rate.

Other problems to the crop caused by an excess of sodium is the formation of crusted seed beds, temporary saturation of the surface soil, high pH, and the increased potential for diseases, weeds, soil erosion, lack of oxygen and inadequate nutrient availability.

6.6.5 *Yield Decrease Due to Poor Quality Water*

Because of the use of poor quality water, crop yield decreases following the equation (Mass and Hoffman 1977):

$$Y = 100 - b(EC_\mathrm{e} - a), \tag{6.8}$$

where Y is the relative crop yield (%), b is the yield loss per unit increase in soil salinity, EC_e is the salinity of the soil saturation extract (dS/m), and a is the soil salinity threshold value (it is the EC_e value for 100% yield potential).

On an average, $EC_\mathrm{e} = 1.5\ EC_\mathrm{w}$

The b value can be determined as:

$$b = 100/(EC_\mathrm{e}\ \text{at}\ 0\%\ \text{yield} - EC_\mathrm{e}\ \text{at}\ 100\%\ \text{yield}). \tag{6.9}$$

By rearranging the (6.8), the maximum allowable EC_e for a particular yield level can be found as:

$$EC_\mathrm{e} = (100 + ab - Y)/b. \tag{6.10}$$

6.7 Coping Strategies in Using Poor/Marginal Quality Irrigation Water for Crop Production

Poor quality water may be used as irrigation water if the harmful effects are off-set by certain management practices, or tolerant crops are cultivated.

6.7.1 *Management Strategies in Using Poor Quality Irrigation Water*

A range of management strategies of varying complexities are available to mitigate the effects of poor quality water. Present scientific knowledge, if judiciously applied, may be adequate for copying with many of the salinity problems resulting from mismanagement of irrigation and drainage.

Undoubtedly, soil salinity is the most prevalent and widespread problem limiting crop production in irrigated agriculture. When irrigated with water of high salinity and sodicity, decreased macro-porosity and reduced soil hydraulic conductivity were exhibited. Significant soil conditioning and leaching of salts would be required to ameliorate or mitigate the effects of previous irrigation to the point of being able to establish economically viable crop production.

6.7.1.1 Leaching

The accumulated salt in the crop root zone (i.e., soil salinity) can be lowered or reduced to a desirable limit by applying more water than the crop actually need for evapotranspiration. The additional water washout and moves the salts (at least a portion) below the root zone. The process is termed as leaching.

The leaching requirement (LR) is the amount of water that must pass through the root zone to reduce the salt to a specific level. The LR can be estimated as (Rhoades 1974):

$$LR = \frac{EC_{\mathrm{w}}}{5(EC_{\mathrm{e}}) - EC_{\mathrm{w}}}, \tag{6.11}$$

where LR is the minimum leaching requirement to reduce the salts within the tolerance (EC_{e}) of the crop with surface methods of irrigation, EC_{w} is the salinity of the applied irrigation water (dS/m), and EC_{e} is the average soil salinity tolerated by the crop as measured on a soil saturation extract (dS/m).

Total water depth (to meet ET and for leaching) for irrigation can be calculated as:

$$WR = \frac{ET}{1 - LF}, \tag{6.12}$$

where WR is the total irrigation depth required (mm), ET is the evapotranspiration (mm), and LF is the leaching fraction (leaching requirement expressed as a fraction of irrigation water).

Leaching requirement can be expressed as absolute amount, or a fraction or percentage of irrigation water.

6.7.1.2 Neutralizing the Effect of Some Elements by Adding Ameliorants

Under soil factors with saline background, where water quality is marginal, amendment through gypsum application can facilitate growing of crops to a certain extent. Details about gypsum application and its calculation procedure have been discussed in chapter “Salinity Management,” Volume 2.

6.7.1.3 Mixing of Different Quality Water

Poor quality water can be mixed with good quality water to change the quality from poor to acceptable/tolerable limit. This approach is only possible where a relatively better quality source is available, and that the better quality supply is not enough to meet the demand. Mixing does not reduce the total solute content, but reduces the solute concentration due to dilution.

The quality of the mixed water can be obtained by using the following equation (adapted from Ayers and Westcot 1985):

$$C_x = (C_1 \times r_1) + (C_2 \times r_2), \tag{6.13}$$

where C_x is the concentration of mixed water, C_1 is the concentration of first category of water, r_1 is the proportion of first category of water, C_1 is the concentration of 2nd category of water, r_1 is the proportion of 2nd category of water and, $r_1 + r_2 = 1$.

The concentration can be expressed as mg/l, ppm, meq/l, or EC_w (dS/m), but must be consistent all throughout.

6.7.2 Workout Problems on Water Mixing and Leaching

Example 6.5. Find the concentration of a water mixture, which is composed of two categories of water. The concentrations of the solutions are 20 and 100 mg/l. The proportions of the categories are 40% and 60%, respectively.

Solution.
We know,

$$C_x = C_1 \times r_1 + C_2 \times r_2$$

Given,
Concentration of 1st solution, $C_1 = 20$ mg/l
Proportion of 1st solution, $r_1 = 40\% = 0.40$
Concentration of 2nd solution, $C_2 = 100$ mg/l
Proportion of 2nd solution, $r_2 = 60\% = 0.6$

Putting the above values, concentration of the mixed water, $C_x = (20 \times 0.4) + (100 \times 0.6) = 14$ mg/l (*Ans.*)

Example 6.6. An irrigator is irrigating a wheat crop with canal water ($EC_w = 0.50$ dS/m), and the water demand for wheat is 300 mm per season. The EC_e is 2.6 dS/m. The irrigator can expand the crop area if additional water is available, but no more canal water is available. Underground water is available but having $EC = 3.9$ dS/m, which is marginal for wheat production. Examine the possibility of mixing groundwater with canal water, so that the irrigator can expand the wheat area.

Solution.

Given, EC of canal water, $EC_w(c) = 0.50$ dS/m

EC of groundwater, $EC_w(g) = 3.9$ dS/m

EC of soil saturation extract, $EC_e = 2.6$

The ET of wheat = 300 mm/season

Now, allowing maximum EC_w of mixed water corresponding to 90% of yield potential.

We have, $Y = 100 - b(EC_e - a)$

Or, $EC_e = (100 + ab - Y)/b.$

Here, a is the salinity threshold value (EC_e value for 100% potential yield) = 2.5 dS/m (assuming for wheat)

b is the yield loss per unit increase in soil salinity, and can be obtained as:

$$b = 100/(\mathrm{EC_e}\ \text{at}\ 0\,\%\,\text{yield} - \mathrm{EC_e}\ \text{at},\ 100\%\,\text{yield})$$

$$= 100/(20 - 2.5) = 5.7\mathrm{dS/m}$$

Thus, EC_e from (A) = 4.25 dS/m

We get, $EC_e = 1.5\ EC_w$

Or, $EC_w = EC_e/1.5 = 2.83$ dS/m

After mixing,

$$EC_w(\mathrm{mix}) = (EC_w - \mathrm{canal} \times r_1) + (EC_w - gw \times r_2)$$

or

$$r_2(EC_w - gw - EC_w - \mathrm{canal}) = EC_w - \mathrm{mix} - EC_w - \mathrm{canal}$$

or

$$r_2 = (EC_w - \mathrm{mix} - EC_w - \mathrm{canal})/(EC_w - gw - EC_w - \mathrm{canal})$$

putting the values,

$r_2 = 0.69$, i.e. 69% groundwater

$$r_1 = 1 - r_2 \qquad [\mathrm{as} r_1 + r_2 = 1]$$

$= 0.31$, i.e. 31% canal water

Thus, canal water can be mixed with up to 69% groundwater. Yield potential would be maintained at about 90%, and the area can be expanded by 69%. In that case, the leaching fraction would be:

$LR = EC_w/(5EC_e - EC_w)$

$= 2.83/(5 \times 425 - 283)$

$= 0.15$

Irrigation water need, $AW = ET/(1 - LF)$
$= 300/(1 - 0.15)$
$= 354.5$ mm

Thus, with 354.5 mm irrigation water of the above mixture, 90% potential yield can be obtained with 67% increased crop area (*Ans*).

6.8 Water Quality of River and Stream

All living things need water. Healthy water contains a balanced amount of nutrients and normal fluctuations in salinity and temperature. It also has plenty of oxygen and little sediment so that underwater living resources can breathe or receive enough sunlight to grow.

Nontidal areas in the bay region are defined as areas where water is not affected by the tides of the ocean. Because so much freshwater flows into the bay, the water quality in no-tidal areas is of extreme importance. Freshwater flows carry nutrients (nitrogen and phosphorus) and sediment to the bay. Though this is a natural process, the actions of people on land can increase the amounts of these stressors.

For proper management and decision making, measurement of water flow and nutrient concentration, load and yield should be measured. Nutrients can reach the nontidal portions of rivers either through point sources or nonpoint sources. Besides the reduction of actions that contribute to nutrient pollution, another defense that can help to protect rivers is a forest buffer. Vegetation near water can consume nutrients.

Sediment can reach nontidal areas through many sources. Dams can trap sediment and prevent it from flowing downstream.

6.9 Water Quality Models and Tools

6.9.1 Models

Water quality modeling involves the prediction of water pollution using mathematical simulation techniques. Water quality models are tools for simulating the movement of pollutants. A typical water quality model consists of a collection of formulations representing physical mechanisms that determine fate and transport of pollutants in a water body. Both single-event and continuous simulation may be performed on catchments having storm sewers and natural drainage, for prediction of flows, stages, and pollutants concentrations. Water quality is modeled by one or more of the following formulations:

- Advective transport formulation
- Dispersive transport formulation
- Surface heat budget formulation
- Dissolved oxygen saturation formulation
- Re-aeration formulation
- Carbonaceous deoxygenation formulation
- Nitrogenous biochemical oxygen demand formulation
- Sediment oxygen demand formulation (SOD)
- Photosynthesis and respiration formulation
- pH and alkalinity formulation
- Nutrients formulation (fertilizers)
- Algae formulation
- Zooplankton formulation
- Coliform bacteria formulation (e.g., *Escherichia coli*)

Each water quality model has its own unique purpose and simulation characteristics. The users are advised to thoroughly review the input requirements, output, and the limitations; and check whether the model serves the purpose for a particular case. Some of the water quality models are mentioned below.

AQUATOX: A freshwater ecosystem simulation model. It predicts the fate of various pollutants, such as nutrients and organic toxicants, and their effects on the ecosystem, including fish, invertebrates, and aquatic plants.

AGNPS: An “agricultural non-point source (AGNPS)” model. It estimates nutrient loads in run-off water for a wide range of storm events.

CORMIX: A mixing zone model that can be used to assess water quality impacts from point source discharges at surface or subsurface levels.

DRAINMOD-N: A “quasi-two-dimentional” model that simulates the movement and fate of nitrogen in shallow water table soils with artificial drainage.

EUTROMOD: A model for managing eutrophication in lakes and reservoirs. The model provides information concerning the appropriate mix of point source discharges, land use, and land management controls that result in acceptable water quality.

WASP7: An enhanced version of the Water Quality Analysis Simulation Program (WASP). It includes kinetic algorithms for the following:

- Eutrophication /conventional pollutants
- Organic chemicals/metals
- Mercury
- Temperature, fecal coliform, and conservative pollutants

QUAL2K: A river and stream water quality model, intended to represent a modernized version of the QUAL2E model.

TWQM: Computes the steady-state, longitudinal distribution of water quality downstream of a reservoir.

QUAL2E: Steady-state, one-dimensional stream water quality model, available from EPA (USA).

BIOMOC: A multi-species solute-transport model with biodegradation.

6.9.2 Tools

Water quality tools include maps and methods.

BASINS: A multipurpose environmental analysis system that integrates a geographical information system, national watershed data, and environmental assessment and modeling tools into one convenient package.

DFLOW: A tool to calculate design flow statistics. It also includes several pages explaining how to use the tool and provides detailed background information.

Economics and Benefits: Estimate the benefits of water quality programs.

WATEQ4F: A program for calculating speciation of major, trace, and redox elements in natural waters.

6.10 Contamination/Pollution of water

6.10.1 Major Sources of Water Contaminants

Water can be of poor quality for irrigation or other intended use because of the amount of impurity it contain or the kinds of impurities present (e.g., salt, suspended solids, chemicals). Water can contain organic substances, heavy metals, and micro-nutrients, which can reduce its aptitude for intended use. The pollution factors can be broadly classified as follows:

1. Micro-biological: Bacteria and other germs.
2. Ionic: Presence of heavy metals.
3. Organic/inorganic compounds: Industrial pollutants, pesticides, dead body, etc.
4. Radioactive: Nuclear waste.

The major sources of water contamination include the following:

- Agricultural fields
- Industrial effluents
- Residential and municipal sources
- Storm water runoffs
- Mining operations
- Radioactive disposals
- Processing of wood

6.10.1.1 Agricultural Field and Rural Areas

The application of inorganic fertilizer, pesticide, insecticide, and herbicide has become an integral part of modern agricultural production. The ultimate fate of these chemicals is the surface water and groundwater. These compounds, especially those with lower solubility, may enter rivers by runoff and erosion and eventually be concentrated in the sediment. The organic pesticides distribute dynamically between organisms, water and particulate matter until a new equilibrium is attained, resulting in another type of pollution.

6.10.1.2 Industrial Effluents

Different chemicals are discharged from industries (medicine, glass, etc.) as effluent. Mercury is discharged from many industrial sources including pulp and paper mills. These effluents are end up into rivers and lakes, and pollute the surface as well as groundwater.

6.10.1.3 Urban Storm Water Runoffs

Storm water discharges are generated by runoffs from land and impervious areas such as paved streets, parking lots, and building rooftops during rainfall and snow events. The water is discharged into streams, lakes, and reservoirs and often contains pollutants such as trash and debris, bacteria and viruses, oil and grease, sediments, nutrients, and metals. Pollutants carried in urban runoff can cause both short-term and long-term adverse water quality impacts on our local water bodies. Most storm water discharges are considered as point sources.

6.10.1.4 Residential and Municipal Sources

Municipal point sources are the largest pollutant sources for rivers, lakes, and estuaries. Contaminants from those sources include metals, phosphates, solvents, and other wastes. The septic tanks or septic systems of residential/municipal areas if improperly used or operated (without treatment) can be a significant source of groundwater contamination.

6.10.1.5 Radioactive Waste Disposal

Radioactive disposal from nuclear plants can contaminate water bodies if it is not disposed in a proper way.

6.10.1.6 Mining Operations

Mining of coals and other resources causes exposure of different single elements and compounds. Because of rainfall and other operations, the contaminants ultimately reach surface and groundwater.

6.10.1.7 Processing of Wood

During the preservation processing of wood, chemicals are used. These ultimately wash out to the water body and contaminate the water.

Pollutant concentrations become diluted when they enter water sources and are further reduced by biological degradation, filtration, and adsorption to soil. Some chemicals, such as the man-made chlorinated hydrocarbons, are very stable in the environment. Some of these compounds accumulate in living organisms and are not readily metabolized and excreted. The impacts of contamination events to lakes and reservoirs are more severe and persistent than streams and rivers because there is not a natural flushing process as is characterized by the flow in streams and rivers. Contamination is even more persistent in groundwater due to the lack of biological degradation. The most biologically active bacteria live within the soil above groundwater.

In contrast to surface water, there is not a lot of mixing when a contaminant enters groundwater. When a contaminant first enters the soil, it will travel down vertically with gravity until contact with groundwater. At this point, it will begin to flow primarily in a horizontal direction. The contaminant will then spread out three-dimensionally. Groundwater does not exhibit turbulent flows as found in surface water. The flow is defined by gravity, pressure, and friction. It is much more constant than surface water. The most effective way of reducing contaminants in drinking water is by controlling it at the source.

6.10.2 Arsenic Contamination: Causes, Consequences, and Mitigation/Remedial Measures

6.10.2.1 Extent of the Problem

Arsenic is widely distributed throughout the earth's crust. There are many countries in the world where arsenic in drinking water has been detected at a concentration greater than the FAO guideline value 0.01 mg/l or the prevailing national standard. These include Argentina, Australia, Bangladesh, Chile, China, Cambodia, Ghana, Hungary, India, Mexico, Peru, Thailand, United States of America, and Viet Nam. Countries where adverse health effects have been documented include Bangladesh, India (West Bengal), China, and the United States of America.

Delayed health effects of exposure to arsenic, the lack of common definitions and of awareness as well as poor reporting in affected areas are major problems in determining the extent of the arsenic-in-drinking-water problem.

Box 6.1: Arsenic Problem in Bangladesh, India, and USA

According to a British Geological Survey study in 1998 on shallow tube-wells in 61 of the 64 districts in Bangladesh, 46% of the samples were above 0.010 mg/l and 27% were above 0.050 mg/l. When combined with the 1999 population, it was estimated that the number of people exposed to arsenic concentration above 0.05 mg/l is 28–35 million, and the number of those exposed to more than 0.01 mg/l is 46–57 million (BGS and MML 2000).

In India, 7 of 16 districts of West Bengal have been reported to have ground-water arsenic concentrations above 0.05 mg/l; the total population in these seven districts is over 34 million (Mandal et al. 1996), and it has been estimated that the population actually using arsenic-rich water is more than 1 million (above 0.05 mg/l).

Environment Protection Agency of the United States of America has estimated that 13 million of the population of USA, mostly in the western states, are exposed to arsenic in drinking water at 0.01 mg/l, although concentrations appear to be typically much lower than those encountered in areas such as Bangladesh and West Bengal (USEPA 2001).

6.10.2.2 Sources of Arsenic

Main sources of arsenic are given below.

Arsenic Containing Rocks

Arsenic, in the earth's crust, is associated with the ores of gold, silver, copper, lead, zinc, nickel, and cobalt. Arsenic is introduced into water through the dissolution of minerals and ores, and erosion from local rocks. The occurrence of arsenic in natural waters is usually associated with geothermal areas, sedimentary rocks of marine origin, weathered volcanic rocks, mineral deposits, and mining wastes.

The common primary arsenic minerals are sulphides with iron, cobalt, copper, nickel etc., which are as follows:

Name	Formula	% As (w/w)
Realgar	AsS	70.0
Orpiment	As_2S_3	61.0
Arsenopyrite	FeS_2FeAs_2	46.0
Cobatite	$CoAsS$	45.2
Niccolitse	$NiAsS$	45.0
Energite	Cu_3AsS_4	19.0

Arsenopyrite is the most common and the most abundant in nature among the above listed minerals. This is how it is considered as principal source of arsenic contamination in groundwater in many areas in West-Bengal, India, and Bangladesh.

Industrial Effluents

Industrial effluents also contribute arsenic to water in some areas. Industrial activities such as petroleum refining, pesticide and herbicide manufacturing, ceramic and glassware industries, metallurgical industries, and organic and inorganic chemical industries contribute significant amounts of arsenic to various sections of the environment. Arsenic is used commercially in alloying agents and wood preservatives. Combustion of fossil fuels is a source of arsenic in the environment through disperses atmospheric deposition.

Inorganic Arsenic

Inorganic arsenic can occur in the environment in several forms but in natural waters, and thus in drinking water, mostly trivalent arsenic (As(III)). Organic arsenic species, abundant in seafood, are much less harmful to health, and are readily eliminated by the body.

Agricultural Use of Herbicides, Pesticides

The use of arsenical pesticides and herbicides can contribute arsenic to natural water-bodies and the ecosystem. Organo arsenic compounds, such as cacodylic acid (hydroxy dimethylarsenic oxide), are used as herbicides, which find entry into streams or lakes through run-offs from land during rainfall. This may further be degraded to arsine by biological action.

Other Sources

Other sources of arsenic are fossil fuels and irrigation practices.

Thus, the natural occurrences along with man-made sources are responsible for increasing concentration in natural waters. Natural arsenic sources are much larger than man-made sources.

Properties of Arsenic

Arsenic is an element of group (V)A according to atomic weight chart, having atomic number 33 and atomic weight 74.9216. It is a metalloid that is having both the properties of metal and nonmetal. It is colorless, odorless, tasteless, and nonirritating gas that causes a rapid and unique destruction of red blood cells and may result in kidney failure. It sublimates at 616°C. Arsenic exhibits a broad range of chemical reactivity with an ability to form alloys with other elements and covalent bonds with carbon, hydrogen, and oxygen. It readily participates in oxidation, reduction, methylation-demethylation, and acid-base reactions.

Arsenic has affinity for iron. It usually forms acompound with sulphur rather than with oxygen and silicon.

6.10.2.3 Forms of Arsenic

Arsenic has three allotropic forms: gray crystalline, black, and yellow. It occurs in four oxidation states, which are as follows:

1. Arsenate (As^{5+}) [pentavalent arsenic, i.e., Arsenic (V)]
2. Arsenite (As^{3+}) [trivalent arsenic, i.e., Arsenic (III)]
3. Arsenic (As^0)
4. Arsinic (As^{3-})

Arsenite is more mobile and more stable than arsenate in aqueous solution especially at pH greater than 7.0. Stability of arsenite increases in reducing condition. Arsenic (III) is 5–10 times more soluble in water than corresponding arsenic (V).

6.10.2.4 Toxic Effects of Arsenic

Toxicity of arsenic is dependent on its oxidation state. The toxicity scale of arsenic decreases in the order of:

Arsine > inorganic arsenic (III) > organic arsenic (V) > arsonium compounds and elemental arsenic.

The toxicity of arsenic (III) is about 10 times that of arsenic (V). The increased toxicity of arsenic (III) relative to arsenic (V) is due to its ability to react with sulfyhydryl groups, thereby increasing its residence time in the body. Arsenic is a protoplasmic poison because of its effect on a sulfyhydryl group of cells interfering with cells enzymes, cell respiration, and mitosis.

6.10.2.5 Causes/Theories of Arsenic Contamination

At present, the well-known theories about the mechanism of arsenic contamination are as follows:

- Oxy-hydration/reduction theory
- Oxidation theory

Oxy-Hydration/Reduction Theory

According to this theory, arsenic is released into groundwater because of the "reduction" of arsenic containing iron-oxyhydroxides, which are coated in mineral grain. This occurs in an environment of low level of dissolved oxygen. The mechanism is illustrated below:

$$\boxed{\begin{array}{c}\text{Arsenic}\\ \text{absorbed with}\\ \text{ferric-}\\ \text{oxyhydroxide}\\ \text{As-FeOOH}\end{array}} + \boxed{\begin{array}{c}\text{Organic matter}\\ (CH_2O)\ \&\\ \text{Carbonic acid}\\ (H_2CO_3)\end{array}} \xrightarrow[\text{metabolism}]{\text{Microbial}} \boxed{\begin{array}{c}\text{Free}\\ \text{arsenic}\\ (As)\end{array}} + \boxed{\begin{array}{c}\text{Ferrous } (Fe^{2+})\\ \text{compound,}\\ \text{bicarbonate }\&\\ \text{water}\end{array}}$$

The underground is gradually becoming oxygen deficient because of contamination with various organic and inorganic pollutants dumped under the ground area making the environment anaerobic. The anaerobic theory is strongly supported by the findings of the groundwater study in Bangladesh conducted by British Geological Survey (BGS).

Oxidation Theory

According to this theory, arsenic is released from arseno-pyrite (As-FeS) to groundwater due to oxidation. The lowering of water table owing to over exploitation of groundwater for irrigation has initiated the release of arsenic. The large sale withdrawal of groundwater has caused rapid diffusion of oxygen within the pore spaces of sediments as well as an increase in dissolved oxygen in the upper part of groundwater. The newly introduced oxygen oxidizes arsenopyrite in the presence of water with the concomitant release of arsenic to groundwater. The mechanism is shown below:

$$\boxed{\begin{array}{c}\text{Arseno-pyrite}\\ (\text{As-FeS})\end{array}} + \boxed{\begin{array}{c}O_2 +\\ H_2O\end{array}} \longrightarrow \boxed{\begin{array}{c}\text{Free arsenic}\\ (As)\end{array}} + \boxed{\begin{array}{c}\text{Ferric Oxy-hydroxide}\\ (\text{FeOOH}) + \text{Hydrogen}\\ \text{sulfide } (H_2S)\end{array}}$$

6.10.2.6 Effects and Consequences of Arsenic Contamination/Poisoning

The impact of arsenic extends from immediate health effects to extensive social and economic hardships that affect, especially, the poor. Costs of health care, inability of affected persons to engage in productive activities and potential social exclusions are important factors.

The main effects of arsenic are given below:

- Health effects
- Effects on crop production
- Social effects

Health Effects

Arsenic is an accumulative, potent, and protoplasmic poison. Chronic poisoning by arsenic compounds leads to loss of appetite and weight, diarrhea alternating with constipation, gastrointestinal problems, peripheral neuritis, conjunctivitis, dermatitis, and sometimes skin cancer. It is also carcinogenic in mouth, larynx, and bladder. The toxic effect of arsenic is dependent on its chemical form, route of entry, age, sex, doses, and duration of exposure. In 1983, the FAO/WHO joint commission of the codex Alimentarius established the maximum acceptable daily intake of arsenic as 2 μg/kg.

The major portion of the absorbed arsenic is excreted through the urine (about 50%), a small portion through face, skin, hair, and nails; and firmly bound to keratin. Although for thousands of years, arsenic in small doses had been used as a medicine, arsenic in drinking water at a level of 0.06 mg/l or more ultimately kills. As a result of several years of low-level arsenic exposure, various skin lesions either in the form of hyper-pigmentation (dark spot), hypo-pigmentation (white spot), and keratoses of the hands and feet may appear. It has been estimated that within the next 20–30 years from arsenic affected, internal cancers such as lung, kidney, liver, and bladder are likely to appear among 10% of those succumbing to the poisoning. People will face slow death as their bodies succumb to the carcinogenic and mutagenic effects of arsenic.

Arsenic can cause toxicity in lower amounts to certain genetically susceptible children. It is also possible that some individuals are able to tolerate higher amounts of arsenic without harm to their health. Thus, “safe” arsenic levels may be not safe at all to those who are sensitive.

Effects on Crop Production

Growth of different crops is retarded at higher level of arsenic. Yield of rice is reduced to a great extent at increased level of arsenic (Delowar et al. 2005; Abedin et al. 2002). In addition, in arsenic affected areas (groundwater and/or soil), the rice grain contain considerable amount of arsenic (0.058–1.83 mg As per kg). Indirect effects of arsenic on yield are due to antagonism between arsenic and essential macro and micro-nutrients in both uptake and metabolic pathways. It also reduces soil bio-functionality. Reduction in yields and yield quality may in turn have consequential impacts on rural livelihoods through reduced farm incomes and indirectly through in nutritional status and associated impacts on human health. In addition, from public health perspectives, the food chain transfer of arsenic is of considerable concern. The provisional tolerable weekly intake value for arsenic established by Joint FAO/WHO Expert Committee on Food Additives (JECFA) in 1988 is 0.015 μg As per kg body weight.

Social Effects

Arsenic contamination has been creating serious social problems for the affected areas. The native people consider arsenic diseases to be contagious. In many cases, the affected people have been ostracized by neighbors, friends, and relatives. The affected children are often barred from attending schools, and the adults are discouraged from attending offices and public meetings. The women suffering from arsenic diseases are the worst victims. Affected married women are no longer considered acceptable as wives because of their skin lesions and are sent back to their parents with their children; thus, unaffected parents and children also suffer socially with the affected females. Thereby, social life is affected due to the curse of arsenic contamination.

6.10.2.7 Mitigation/Remedial Measures of Arsenic Contamination

Whatever may be the actual cause of arsenic contamination, removal of this toxic ingredient is essential. There are no proven technologies for the removal of arsenic at water collection points such as wells, hand-pumps, and springs. Simple technologies for household removal of arsenic from water are few and have to be adapted to, and proven sustainable in each different setting. Some studies have reported preliminary successes in using packets of chemicals for household treatment. Some mixtures combine arsenic removal with disinfection.

The technology for arsenic removal for piped water supply is moderately costly and requires technical expertise. It is inapplicable in some urban areas of developing countries and in most rural areas world-wide. New types of treatment technologies including co-precipitation, ion exchange, and activated alumina filtration are being field-tested.

Strategic Measures

The following strategies for escape/mitigation/remedy of arsenic contamination may be employed (single or in combination, depending on the situation):

1. Sinking tube-wells at arsenic-free zone/layer (escaping arsenic contaminated zone).
2. Removal of arsenic from water (through arsenic-filter and other techniques).
3. Use of alternative safe water options.
4. Growing arsenic-consuming plants (e.g., Brake Fern).
5. The fern Pteris vittata (Brake fern) is extremely efficient in extracting arsenic from soils and translocating it into its aboveground biomass. Perhaps it can be used in the remediation of arsenic-contaminated water too.
6. Detoxify the arsenic sludge.
7. Cultivating arsenic-tolerant crop variety.

8. Consuming sufficient fleshy vegetables, which lessen the effect of arsenic in human body.
9. Restricting the use of arsenic containing herbicides/pesticides.
10. Restricting and managing (detoxify) the arsenic containing industrial disposal.
11. Restricting /lessening the withdrawal of underground water where arsenic is found, and facilitating the use of surface and rainwater.
12. Initiating programs (technical and structural) and extension services to promote the use of surface water and rainwater harvesting as an alternative.

Removal Techniques of Arsenic from Water

Available treatment technologies for removal of arsenic from water and wastewater include the following:

- Coagulation
- Softening
- Ion exchange
- Reverse osmosis
- Oxidation and filtration
- Adsorption

Coagulation

Coagulation is a popular method for arsenic removal. The effective coagulants are iron, copper, silver, magnesium, sodium, and aluminium salts. From different experimental results, it is reveled that ferric chloride and alum perform better.

Gulledge and O'conner (1973) observed arsenic removal as a function of pH and coagulation dose. The arsenic removal was accomplished by adsorption on aluminium and ferric hydroxide and by increasing the coagulant dose. There was a consistent increase in the removal of arsenic at all pH levels. McNeill and Edward (1995) observed that in the process of coagulation, immediately after alum addition, soluble As(V) concentration decreased by 6–74%, and additional soluble arsenic was removed during chlorine addition or filtration process. Enhanced arsenic removal at lower pH was attributed to formation of higher concentrations of particulate aluminium. Arsenic removal efficiencies were affected by high sulphate content in the raw water.

Softening

Removal of arsenic can be achieved by precipitative softening process. Use of lime softening with powdered coal additive to lower arsenic concentration (As(III) 0.60 mg/l) below the guideline value of 0.05 mg/l was reported. Laboratory tests suggested a lime dosage of 1,250 mg/l at pH 11.5 to achieve 90% arsenic removal.

$Mg(OH)_2$ is very effective for sorbing arsenic. Carbonate can interfere with arsenic removal by iron.

Ion exchange

Anion exchange can be recommended for water with total dissolved solids <500 mg/l or sulphate <25 mg/l. To make ion exchange process effective, As (III) has to be oxidized to As(V) prior to treatment.

Reverse Osmosis

Reverse osmosis system comprises a prefilter and/or activated carbon filter followed by reverse osmosis membrane, a storage tank and a granular activated carbon systems. The performance of low pressure, reverse osmosis system is good in lowering the arsenic concentration than that of high pressure systems. The advantage of reverse osmosis is not confined to the removal of arsenic but also it removes the other constituents in water. The main disadvantage of reverse osmosis is the productions of more quantity of reject water.

Oxidation and Filtration Process

Oxidation and filtration as a method of arsenic removal is well documented. Oxidation can be performed by sodium hypochlorite, manganese oxide, ferric chloride, etc. Arsenic removal is supported by iron content in the raw water and for complete oxidation of As(III) to AS(V).

Adsorption

Removal of arsenic from water by adsorption can be done using low cost adsorbent materials such as sand, rice hush, fly ash, crushed coconut shell, wood charcoal, bituminous coal, kaolonite, saw dust carbon, coconut husk carbon, and activated alumina, modified alumina, etc. Some studies have shown that sand is the best for overall performance.

A range of arsenic removal units have been developed by various researchers based on the above principles (e.g., Goswami and Das 2001; Karim 2003; Safiullah et al. 1996, 2000). Some simple and indigenous approaches for arsenic removal are described below.

Simple and Indigenous Approaches for Arsenic Removal

Various types of alternative options have been identified for arsenic safe drinking water by the researchers.

Decantation-Filtration Method

Iron concentration 10–20 times higher than arsenic concentration is suitable to remove arsenic in this method. The use of naturally occurring iron in groundwater is the most promising in the removal of arsenic by decantation method followed by filtration.

In this method, the water containing As-Fe is taken into a bucket from the contaminated tube well. The bucket is covered and kept overnight or 12 h stagnantly. As-Fe flocks are observed to be accumulated at the bottom of the bucket. The upper two-third portions can easily be used as relatively safe arsenic-iron water after filtering through a coarse cloth. It is advised that the lower one-third portion be discharged into a surface-hole containing cows' dung.

The chemistry involved in this method is that, ferrous ion (Fe^{+2}) is initially present in a dissolved state in groundwater, which plays the active role in removing arsenic with other settle-able solids. In contact with air during purging of the tube and pouring of water into bucket, Fe (II) is oxidized to Fe (III) and precipitates as $Fe(OH)_3$. There is a possibility of oxidizing As(III) to AS(V) by air within the pH range 7.26–7.86. Some studies show that both species of As are strongly absorbed on iron oxides. Therefore, arsenic is removed through the adsorption and precipitation process.

Pond sand filter

Surface water source is arsenic free in most of the arsenic affected areas. But this water is extremely polluted by pathogenic micro-organisms and other serious contaminants. Thus, all surface water sources need extensive treatment. The establishment of treatment plants and water supply systems for scattered rural areas in the third world poor people is not feasible because of the cost. The prospective way to get arsenic-safe drinking water from surface source is the pond sand filter.

In this method, a concrete tank is built near a protected pond, having three unequally divided chambers. Pond water is supplied into the chambers. Small pieces of bricks and dry coir are placed in the first chamber for removing dirt, whereas the second chamber contains sand gravel. Water runs from first to second chamber and reserved in the outlet chamber. Clean water is received through the tap connected to the outlet chamber. To protect the chambers from external contaminants such as leaves, dusts, and birds' excreta, the tank should be covered.

Three Pitchers Methods

A simple three pitchers (*Kolshis*) method is an indigenous technology, which is low-cost and can be constructed with locally available materials (and is also locally available in third world countries). The removal technology is based on adsorption-filtration method. The pitchers are staked one by one (vertically) in a frame or holder. The first pitcher contains 2.0 kg of coarse sand at the top and 3.0 kg of iron fillings in the bottom. In the second pitcher, 2.0 kg of coarse sand with 1.0 kg of charcoal are layered. Water runs from one pitcher to another through the hole made at the bottom.

A piece of synthetic cloth is placed on the hole of the pitcher to prevent solids. Contaminated water runs through the top pitcher. Water can flow through this system continuously. The third pitcher is for collecting the filtered water.

6.10.2.8 Challenges and Needs

The challenges are our understanding of the contamination process of As and development of new technology for removal. Simple, reliable, low-cost equipment is needed for field measurement for arsenic. Robust affordable technologies for arsenic removal at wells and in households are necessary. Increased availability and dissemination of relevant information is also necessary.

6.11 Protecting Water Quality

6.11.1 Protection Measures Against Potential Sources of Contamination

A potential source of contamination of water may be either apoint source or a nonpoint source. Point source pollution is a type of pollution that can be traced to a single source, such as pipes, wells, or ditches. Pollution from point and nonpoint municipal and residential sources such as wastewater treatment plant and storm water discharges and runoff from lawns, gardens, and golf courses can contaminate drinking water sources.

The goal of source water protection is to prevent contamination. Source water protection means different things in different situations. This is because the threats to drinking water sources and the means to address those threats are site specific and most effectively implemented at the local level, with assistance from the government and private stakeholders.

Communities can implement groundwater protection through wellhead protection programs and surface water protection programs that use watershed management strategies. These programs involve assessing the problems in the protection area, identifying and prioritizing management measures for those problems, and then implementing the management measures.

The first two steps in protecting source water are to identify the geographic areas that most need protection and to inventory the potential sources of contamination in those areas. Source water protection planning usually involves a team of interested stakeholders. Many programs and organizations have some responsibility for water quality and land use planning at the local level. These can range from a town's conservation commission or local country extension agency to state agencies, nonprofit organizations, and federal agencies such as the forest service.

Some programs and organizations work specifically with small communities and water systems.

The following methods may be adopted for protecting contamination of water from different sources:

6.11.1.1 Controlling Commercial and Industrial Sources

Commercial and industrial sources of contaminants may be protected by making storage tanks (aboveground or underground). Aboveground storage tanks (AST) or other containers that are above the ground, partly buried, or in subterranean vaults. ASTs can include floating fuel systems. Underground storage tanks (UST) comprise tanks and any related underground piping systems that have at least 10% of their combined volume underground.

6.11.1.2 Residential and Municipal Sources

Septic tanks or septic systems are used to treat and dispose of sanitary waste, which is wastewater from kitchens, clothes washing machines, and bathrooms. when properly sited, designed, constructed, and operated, septic systems pose minimal threat to drinking water sources. On the other hand, improperly used or operated systems can be a significant source of groundwater contamination.

6.11.1.3 Storm Water Runoff

Storm water discharges are generated by runoff from land and impervious areas such as paved streets, parking lots, and building rooftops during rainfall and snow events. They often contain pollutants in quantities that could adversely affect water quality. Most storm water discharges are considered as point sources. The primary method to control storm water discharges is the use of best management practices.

6.11.1.4 Agricultural and Rural Sources

Nonpoint source pollution comes from many diffuse sources and is caused by rainfall or snowmelt water moving over and through the ground. As the runoff moves, it picks up and carries away natural and human-made pollutants, depositing them into lakes, rivers, wetlands, coastal waters, and even underground sources of drinking water. Runoff contaminated with fertilizer and pesticides from agricultural activities and farming practices is a leading source of nonpoint source pollution and can have significant impacts on vulnerable aquifers. Voluntary programs and best management practices are the most effective tools for controlling agricultural and rural nonpoint source pollution.

6.11.2 Management Measures

An array of different source-water protection methods may be employed to prevent contamination of their drinking water supplies.

6.11.2.1 Regulatory Approach

Regulatory approach involves regulations and ordinances, such as prohibiting or restricting land uses that could release contaminants in critical source water areas. Land uses that pose a risk to source water can be controlled or moved from sensitive areas. Land use prohibition can be aimed at controlling activities that use dangerous substances or the materials themselves. Examples include prohibiting gas stations in sensitive areas, prohibiting septic systems with reservoir setback zone, or placing specific restrictions on the application of pesticide, manure, and sludge. Another way to implement protection is through construction and operating standards. This can involve the use of constructed devices, operating and maintenance practices, or product and waste disposal procedures.

6.11.2.2 Land-Use/Land Acquisition

Purchased land or conservation easements can serve as a protection zone near the drinking water source. In most countries, public water systems are eligible for loans from the Drinking Water State Revolving Fund for this purpose. Local land trusts, community groups, or others should work cooperatively with local water supplies to identify properties that qualify for the funding or offer their expertise in negotiating acquisitions from willing sellers.

6.11.2.3 Education

Education of general mass people (regarding causes, consequences and protective measures of water contamination) can increase awareness of threats to sources, encourage voluntary source water protection, and build support for regulatory initiatives. The first step in a public education effort is to notify business and households that they are in a source water protection area. The annual report of the drinking water suppliers can be used as a vehicle to inform consumers about protection efforts planned or under way and enlist their support.

6.12 Treatment of Water

If the quality of water is not within the permissible limit for the intended use, it should be purified before use. Water treatment is the process of removing contaminants from the water. The goal of water treatment is to reduce or remove all contaminants that are present in water.

Water treatments involve the removal of solids, bacteria, algae, plants, organic, and inorganic compounds. Converting used water into environmentally acceptable water or even drinking water is termed as wastewater treatment.

6.12.1 Different Methods of Treatment

Treatment approaches can be divided into three general types:

- Physical
- Chemical
- Biological

Many processes exhibit both physical and chemical aspects and so are sometimes called physical/chemical or physio-chemical treatment. The required treatment depends on the application of water.

Method of treatment to be applied depends on the source type and quality. The first step in the selection of any treatment process for improving water quality is to thoroughly define the problem and to determine what the treatment process is to achieve. In most cases, either regulatory requirements or the desired reuse of the water is the driving force in selecting for a particular water. A thorough knowledge and understanding of these water quality criteria is required prior to selecting any particular treatment process. In the treatment of water, knowledge of chemistry, biology, and physics are involved.

For drinking water supplies, a variety of treatment processes may be required to remove contaminants from water. The most commonly used processes include filtration, flocculation and sedimentation, and disinfection for surface water. Some treatment processes include ion exchange and adsorption.

6.12.2 Physical Treatment

Several physical processes aim to remove suspended particulate matter. Subsurface drainage water itself is usually low in suspended particles. These processes might be used in an overall treatment process for the removal of particulates formed in another stages of the treatment, such as removal of bacteria from a biological system or removal of precipitates formed in a chemical treatment process.

Particle removal unit processes include sedimentation, flotation, centrifugation, and filtration. Filtration further includes granular media beds, vacuum filters, belt presses, and filter presses.

6.12.2.1 Sedimentation

Sedimentation occurs naturally in reservoirs and is accomplished in treatment plants by basins or settling tanks. Sedimentation let the water sit around to let the flocculated or coagulated particles to settle out. Plain sedimentation will not remove extremely fine or colloidal materials within a short time. The process is used principally as a preliminary to other treatment methods.

6.12.2.2 Filtration

Filtration is the passing of water through a porous media. Filtration removes particles such as clays and silts, natural organic matter, precipitates from other treatment processes, iron, manganese, and microorganisms. The amount of removal is a function of the filtering media. Thus, the choice of filters depends on the required cleanness (quality) and the filtering speed. Coarse, medium, and/or fine porous media have been used depending on the requirement. The flow required for filters can be achieved using gravity or pressure. In pressure filtration, one side of the filter medium is at high pressure than that of the other. To remove the clogged portion of the filter, reversing the flow through the bed and washing out is required. The process is termed as back washing. During the process, the solid should be removed out of the system. Otherwise, the filters must be replaced. Filtration clarifies water and enhances the effectiveness of disinfection.

6.12.2.3 Adsorption

Adsorption is the process of removing soluble contaminants by attachment to a solid. A common example is the removal of soluble organic compounds via adsorption onto granular activated carbon (GAC). GAC is useful for its ability to remove a wide range of contaminants. Certainly, if pesticide were a concern for the drainage water being examined, the use of GAC adsorption would be a leading candidate for treatment.

Another treatment for removing volatile compounds of water is air stripping. In a conventional counterpart air stripping operation, the contaminated water is distributed at the top of a tall reactor vessel that is packed with materials or structures with a high surface area. As the water moves downward, clean air is introduced at the bottom of the reactor and moves upward. As the water and air make contact, volatile compounds are transferred from the liquid phase to the gaseous phase according to gas transfer theory.

6.12.2.4 Aeration

Oxygenation is the main purpose of aeration. Other purposes include removal of carbon dioxide, volatile organic substances, taste producing gases such as ammonia, hydrogen sulfide, and volatile organic compounds.

6.12.2.5 Distillation

Distillation is a thermal process used for salt removal. Heat is used to vaporize the water, leaving the salts behind. The water vapor is condensed to high quality water. The process is energy intensive.

6.12.2.6 Reverse Osmosis

Reverse osmosis is used for desalination applications. If a compartment containing relatively diluted solution is connected to another compartment containing a concentrated solution by a semipermeable membrane, water molecules move from the dilute solution to the concentrated solution. The process is termed as osmosis. Now, if pressure is applied in the higher concentration solution, water molecules will migrate from the higher concentration solution to the lower concentration solution. The method is termed as reverse osmosis water filter system. With this technique, water with higher concentration is discharged.

6.12.3 Chemical Treatment

Chemical treatment includes disinfecting, coagulation, ion exchange, softening, etc. Disinfection kills most harmful organisms and pathogenic bacteria. Chlorine is the most commonly used disinfecting agent. Other disinfectants are chloramines, chlorine dioxide, ozone, silver ions, and ultraviolet radiation.

6.12.3.1 Flocculation/Coagulation

It is the water treatment process that combines or coagulates fine particles into larger particles, which settle out of the water (to the bottom) as sediment. Alum and iron salts or synthetic organic polymers, lime, and furic chloride are commonly used to augment coagulation. Sedimentation or settling occurs naturally as flocculated particles settle out of the water.

6.12.3.2 Ion Exchange

This process is used to remove inorganic contaminants if they can not be removed adequately by filtration or sedimentation. It can be used to remove nitrate, fluoride, chromium, arsenic, uranium, and radium. It can also be used to treat hard water.

6.12.3.3 Softening

Softening means removal of materials that cause “hardness” (such as calcium and magnesium). The water is treated with lime and soda ash to precipitate the calcium and magnesium as carbonate and hydroxide, after which the water is filtered. In an alternative method, the water is passed through a porous cation exchanger, which has the ability of substituting sodium ions in the exchange medium for calcium and magnesium in the water.

6.12.4 Biological Treatment

Biological systems use microorganisms that consume and destroy organic compounds as food source. Biological treatment of waste water and domestic sewage water is used to lower the organic load of soluted organic compounds. There are two main categories: aerobic treatment and anaerobic treatment. Organic load is defined by the biological oxygen demand. In aerobic systems, the water is aerated with compressed air. In some cases, it may be done with oxygen. Anaerobic systems run under oxygen free condition.

If a reservoir or stream is rich/toxic in certain elements (such as ammonia, phosphate, arsenic), then specific plant species that abstract/absorb the toxic element can be grown. In this way, the water can be applied for the intended use.

6.12.5 Water Purification in a Treatment Plant

In a typical municipal water treatment process, water first flows through pumps (from rivers or reservoirs) to a rapid mix basin, then to a flocculation basin, to a settling/sedimentation basin, through filters to a clear well, then disinfection, filtration, after that to storage tanks, and finally to the end users. Some treatment plants may avoid/eliminate one or more processes depending on the quality of input water. A schematic of the pathway of a water treatment plant is given in Fig. 6.3.

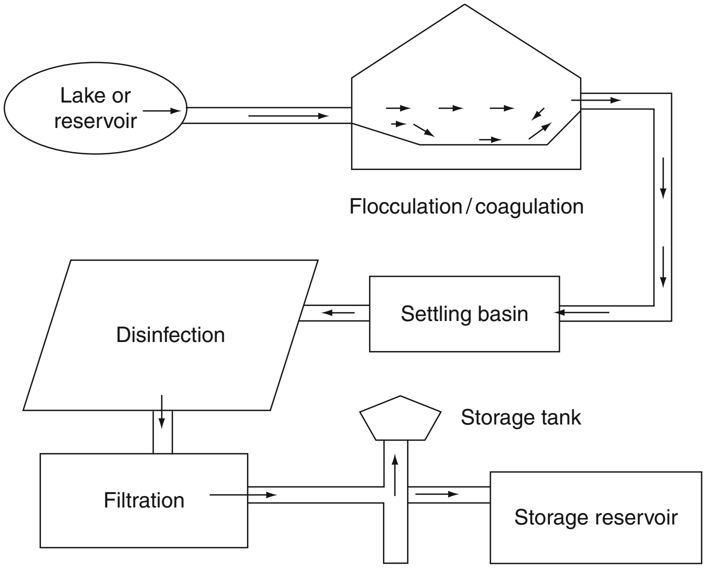

Fig. 6.3 Schematic of treatment processes in a water treatment plant

Relevant Journals

- Journal of Hydrology (Elsevier)
- Hydrological Sciences Journal (Blackwell)
- Journal of Water Chemistry and Technology
- Water International
- Water Quality, Exposure, and Health
- Water Quality and Ecosystem Modeling
- Water and Environment Journal
- Water Science and Technology
- Journal of Contaminant Hydrology
- Journal of Food, Agriculture & Environment
- Environmental Pollution (Elsevier)
- Journal of Environmental Quality
- Environmental Science & Technology
- Environmental Health Perspective
- Bangladesh Journal of Environmental Science
- Agricultural Water Management
- Water Resources
- Advances in Water Resources
- Water Resources Bulletin (American Water Works Association)
- Current Science
- Science and Total environment

Relevant FAO Irrigation and Drainage Papers

- FAO Irrigation and Drainage Paper 29 Rev.1 (Water Quality for Agriculture)
- FAO Irrigation and Drainage Paper 48 (The Use of Saline Water for Crop Production)
- FAO Irrigation and Drainage Paper 47 (Waste Water Treatment and Use in Agriculture)

Questions

1. What are the sources and uses of water?
2. Briefly describe the unique characteristics of water.
3. What is a hydrologic cycle? Narrate the hydrologic cycle with asketch.
4. What is meant by “Water quality”? What are the factors that affect the quality of water?
5. What factors does the suitability of water depend upon? Write down the indicators/parameters of water quality.
6. Briefly discuss the water quality indicators/parameters.
7. What do you mean by “Water quality standard”? Briefly describe the general guidelines of water quality for irrigation as suggested by FAO.
8. Describe different techniques of checking the correctness of water analysis.
9. A groundwater has the following chemical composition (mg/l, if otherwise not stated): EC= 4.1 dS/m, $\mathrm{Ca2^{+}} = 78$, $\mathrm{Mg2^{+}} = 20$, $\mathrm{K^{+}} = 21$, $\mathrm{Na^{+}} = 29$, $\mathrm{Fe3} = 1.2$, $\mathrm{CO32^{-}} = 25$, $\mathrm{B} = 1.5$
   $\mathrm{SO42^{-}} = 31$, $\mathrm{NO3^{-}} = 8$, $\mathrm{HCO3^{-}} = 195$, $\mathrm{As} = 0.10$.

(a) Classify the water quality for irrigation on the basis of EC, SAR, RSC, and H_T.
(b) Comment on the suitability of the water based on bicarbonate, sulphate, iron, and chloride for agro-based industrial usages.
(c) Comment on the standard of the water for human drinking based on Arsenic and nitrate concentration.

10. What are the major problems of using poor quality irrigation water?
11. Describe the strategies to cope with poor quality irrigation water for crop production.
12. State the role of water quality model in managing the water quality problem. Name some water quality models in use.
13. What are the sources of water contamination? Describe the processes of water contamination.
14. Describe the extent and severity of arsenic contamination.
15. What are the sources and mechanisms of arsenic contamination?
16. Briefly describe the mitigation measures of arsenic contamination. What are the challenges remaining in controlling arsenic contamination?
17. What are the measures to be adopted to protect the quality of water?

18. Describe in brief the different treatments methods to purify the poor quality water.
19. Draw a sketch of a water treatment plant

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Chapter 7
Field Water Balance

In every business, there are some types of accounting procedure. In fact, it is essential for a good business, not an option. For water, we also need a good accounting of water supplies, changes in storage, and water destinations for proper management of the resource. For irrigation engineers, proper irrigation scheduling – both timing and amount, control of runoff, minimizing deep percolation, and the uniform application of water – are of primary concern. In field level, water requirements of the plants are met by the storage of soil, supplies from irrigation and rainfall, and to some extent, from shallow groundwater tables. Losses of water from the field include surface runoff from the field, deep percolation out of the root zone, transpiration by plants, and evaporation from the soil surface.

Field water supply has been a major focus of agricultural research and management. The soil-water balance is a widely used method of tracking soil water supply in a field. Water balances are essential for making wise decisions regarding water conservation, water management, and irrigation scheduling. Water conservation implies that within the boundaries of interest, the available water is to be conserved. Accurate computation of water balance can help to avoid past errors and improve for the future. The components of water balance change over time, from day to day, from year to year, etc. The components of field water balance are described in detail (concept, importance, measurement procedure, indirect estimation, limiting conditions, etc.) in this chapter.

7.1 Concepts, Sketch, and Mathematical Form of Field Water Balance

7.1.1 Concept of Field Water Balance

The field water balance is an account of all quantities of water added to, subtracted from, and stored within a given volume of soil during a given period of time in a given field. The water balance is merely a detailed statement of the law of

M.H. Ali, *Fundamentals of Irrigation and On-farm Water Management: Volume 1*,
DOI 10.1007/978-1-4419-6335-2_7, © Springer Science+Business Media, LLC 2010

conservation of matter, which states simply that matter can neither be created nor destroyed but can only be changed from one state or location to another. It is a mass balance of the flow and storage of water in surface soil (for a particular depth) per unit area basis, using the hydrologic equation:

$$\text{Inflow} - \text{Outflow} = \text{Change in storage}$$

Since no significant amounts of water are decomposed or composed in the soil, the water content of a soil profile of finite volume can neither increase without addition from the outside (as by infiltration or capillary rise), nor can it diminish unless transported to the atmosphere by evapotranspiration or to deeper zones by drainage.

Water balance calculation requires two types of boundaries: (i) physical or spatial boundary, and (ii) temporal (time) boundary. Water balance can be studied for a field, farm, irrigation district, or a hydrological basin. The principle is the same for all units, but one must specify which boundary is being talked about when making computations. Similarly, a time boundary should also be specified.

7.1.2 Mathematical Formulation

The general water balance equation at the field plot level can be written from the mass conservation law, over any time period, as:

$$\text{Mass in}-\text{flow} = \text{Mass out}-\text{flow} \pm \text{change in storage}$$

or

$$P + I + U_{\mathrm{w}} = R_{\mathrm{s}} + D + \mathrm{ET}(\text{or } E) \pm \Delta S \tag{7.1}$$

or

$$\mathrm{SW}_{\mathrm{i}} + P + I + U_{\mathrm{w}} = \mathrm{SW}_{\mathrm{f}} + R_{\mathrm{s}} + D + \mathrm{ET}(\text{or } E), \tag{7.2}$$

where P is the rainfall/precipitation; I, the irrigation water applied; U_{w}, the upward flux or capillary rise into the root zone; R_{s}, the surface runoff from the field plot; D, the deep percolation or downward drainage; ET, the evapotranspiration from cropped soil; E, the evaporation from the bare soil; ΔS, the change in soil moisture storage in the soil profile (i.e., $\mathrm{SW}_{\mathrm{i}} - \mathrm{SW}_{\mathrm{f}}$); SW, the soil-water content within a defined root zone; and f and i subscripts represent the end (final) and beginning (initial) of a time period, respectively.

All quantities are expressed in the same unit (in terms of volume of water per unit area, or equivalent depth units) during the period considered.

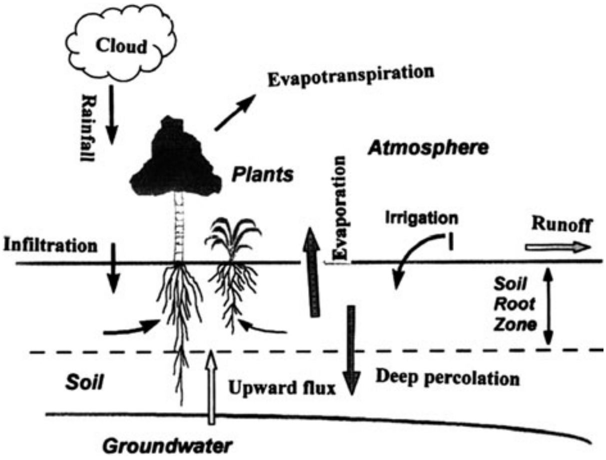

Fig. 7.1 Schematic of field water balance

Although the field water balance may seem simple and readily understandable, it is still rather difficult to measure in practice. A schematic of the components of field water balance is shown in Fig. 7.1.

7.1.3 Limiting Conditions of the Water Balance Components

7.1.3.1 Upward Flux

Upward flux may occur from the free or unconfined water-table, purched water-table, saturated zone, or unsaturated moisture flow from beyond the crop root zone. Upward flux depends on the depth to water-table or saturated zone, the texture (i.e., pore size) of the soil, moisture (i.e., potential) difference between the root zone and the zone adjacent to the root, etc. If the depth to the free water-table or saturated zone in the field never goes closer than 2.5 m from the crop root zone, upward flux from the water-table to the root zone may be zero, but unsaturated moisture flow or moisture migration may occur. Under such conditions, if the crop period is short, the upward flux may be neglected.

7.1.3.2 Surface Runoff

Surface runoff depends on the rainfall amount (intensity and duration) or irrigation amount, history of irrigation or rainfall, and the bund height of the field plot. Surface runoff can be made zero if irrigation or rainfall water is protected by providing sufficient height ($\sim$30 cm) for bunds.

7.1.3.3 Deep Percolation

If water is applied to compensate the root zone moisture deficit ($I <$ SMD), deep percolation may be assumed to be negligible.

If U_{w}, R, D becomes zero or negligible, then (7.1) reduces to:

$$I + P = \mathrm{ET} \pm \Delta S. \tag{7.3.}$$

During dry spells, without rain or irrigation, the above equation becomes:

$$\Delta S = \mathrm{ET}. \tag{7.4}$$

In a larger sense, any soil layer of interest forms a part of an overall hydrologic cycle. In principle, a water balance can be computed for a small sample of soil or for an entire watershed. From an agricultural point of view, it is generally most appropriate to consider the water balance of the crop root zone. The root zone water balance can be expressed in integral form (similar to field water balance):

$$\Delta S + \Delta V = (P + I + U_{\mathrm{w}}) - (R_{\mathrm{s}} + D + \mathrm{ET}), \tag{7.5}$$

where ΔV is the water incorporated in the plants (as metabolic activities and/or change in plant water), which is relatively unimportant and may be neglected.

The upward capillary flow U_{w} and the downward drainage D can be included under the symbol D; D is negative if capillary rise occurs and positive when drainage is present. Thus the (7.5) can be written as:

$$\Delta S = P + I \pm D - R_{\mathrm{s}} - \mathrm{ET}. \tag{7.6}$$

The time rate of change in soil moisture storage can be written as:

$$\frac{\mathrm{d}s}{\mathrm{d}t} = p + i \pm d - r_{\mathrm{s}} - et. \tag{7.7}$$

Here, each of the lowercase letters represents the instantaneous time rate of change of the corresponding integral quantity of (7.6).

7.2 Determination of Different Components of Water Balance

7.2.1 Evapotranspiration

In a crop field, evaporation from the soil and transpiration through plants occur simultaneously. It is not easy to measure them separately and for that reason, they are named together. Evaporation from the soil surface of the crop field and the transpiration through the crop plant in a combined manner is termed as evapotranspiration (ET).

Irrigation water is to be applied in a manner that matches the crop needs of ET. Thus, irrigation scheduling requires estimation of daily crop evapotranspiration with accuracy. Evapotranspiration of crops varies substantially over the growing season mainly due to variations in crop cover and climatic condition. It also differs among crops. The knowledge of crop water demand (i.e., ET) is an important practical consideration in the planning, designing, and operation of irrigation and water management systems.

7.2.1.1 Factors Influencing Evapotranspiration

The water loss by evapotranspiration from a crop field is influenced by the following:

1. Crop factor
2. Weather factor
3. Soil factor
4. Management factors

Crop Factor

Crop factors influencing ET include crop type, variety or species, stage of crop development (depth of root zone, leaf area), etc. The major plant or crop factors influencing ET are as follows:

(a) Crop characteristics
(b) Leaf number and leaf area
(c) Leaf architecture
(d) Leaf rolling or folding
(e) Number and size of stomata
(f) Stomatal closure
(g) Root – its depth, density, pattern

Crop Characteristics

Crop characteristics include resistance to water transport, roughness, rooting depth, root density, plant height, ground cover, reflection characteristics of solar radiation, etc.

Leaf Number and Leaf Area

The ET is influenced by leaf number and total leaf area. The more the leaf surface area, the greater the ET. However, there is less increase in ET for each unit increase in leaf area index (LAI). The ET will not increase with the increase in LAI after a certain limit (normally when 80% of the incoming solar radiation is intercepted).

Leaf Architecture

Leaf architecture of a plant influences radiation interception and thus ET.

Leaf Rolling or Folding

If the leaf area is reduced by leaf rolling, the ET will be reduced consequently.

Root Factor

The total availability and extraction of soil moisture by the crop is dependent on root depth, its density, and type of the root. Roots having deeper rooting depth and high density can extract more soil moisture, and thus increase ET.

Stomatal closure

The stomata open in response to light; thus, ET increases with solar radiation. The daily pattern of ET starts to decrease in the late afternoon because of less light intensity and decreasing temperature.

Weather Factor

Weather factors influencing ET include solar radiation, temperature, humidity, wind-speed, and day-length. The mode or mechanism of weather factors influencing ET has been described in detail in Chap. 3 (Weather).

Soil Factor

Soil factors such as soil moisture reserve, moisture release property, soil salinity, fertility level, presence of impermeable layers in soil horizons, etc. influence ET rate. Under high soil moisture conditions, ET increases with the increase in atmospheric demand. With the constant atmospheric demand, ET decreases with the decrease in soil moisture. Mode of influence of soil moisture on ET has been shown in Chap. 8 (Soil–water–plant–atmosphere relationship). Limiting soil moisture causes changes in the relationship among soil moisture, ET, water flow through the plant, and stomatal closer.

Management Factor

Management factors influencing ET include mulching, shading, weeding, irrigation and/or fertilizer application, control of disease and pests, etc. High or optimum input management influences the crop development and thus influences evapotranspiration. Mulching and shading reduce soil evaporation loss by retarding solar radiation. Mulching also creates a boundary layer effect for the transfer of water vapor from the soil surface.

7.2.1.2 Determination of ET

Evapotranspiration can be determined directly by field experimentation, field lysimeter, or it can be estimated indirectly from weather data and the predetermined crop coefficient values.

Direct Measurement

Field Measurement

In a field experimental set up, several (at least one) access tubes should be installed for each plot at different depths (up to 105 cm), and soil moisture can be monitored with neutron moisture meters or other types of instrument. If soil moisture is determined gravimetrically, it may be converted into volumetric percentage by multiplying it with soil bulk density. The ET for a particular time period can be expressed in the following form of equation:

$$\mathrm{ET}_{\Delta T} = SM_1 - SM_2 + IR + R_\mathrm{e} + U - D - \mathrm{SR}, \tag{7.8}$$

where $\mathrm{ET}_{\Delta T}$ is the ET for the time period ΔT (between time of SM_1 and SM_2 reading, mm); SM_1, the soil water content of the field plot root zone at the beginning of the time period ΔT (mm); SM_2, the soil water content of the field plot root zone at the end of the time period ΔT (mm); IR, the irrigation amount applied within the time period (mm); R_e, the effective rainfall within this time period (mm); U, the upward flux or capillary rise within the time period (mm); D, the deep drainage or percolation within the period (mm); and SR, the surface runoff within the period (mm).

The parameters of right-hand side of the above equation should be measured and used to obtain ET. Estimation of ET using the field water balance approach should be done for not less than 7 days. But with the weighing lysimeter, hourly or daily estimates of ET can be made.

Total soil moisture within the root zone at a particular time may be calculated as:

$$SM_\mathrm{t} = \sum_{i=1}^{n} (V_{\mathrm{v}i} \times Z_\mathrm{i})/100, \tag{7.9}$$

where SM_t is the total profile soil moisture within the crop root zone, in m depth, V_{vi} is the volumetric moisture content in percent for the layer i, Z is the depth of soil layer i (m), and n is the total number of soil layers within the root zone (nos).

For gravimetric moisture determination, it is given in the form:

$$SM_t = \sum_{i=1}^{n} \left(V_{wi} \times \rho_{si} \times z_i\right) \times 100, \tag{7.10}$$

where V_{wi} is the percent moisture content in weight basis (w/w) for the layer i, ρ_{si} is the bulk density of soil of layer i, and the density of soil-water is considered as 1 gm/cc or 1,000 kg/m^3.

Measurement by Lysimeter

Concept and definition of lysimeter

The term "lysimeter" is derived from the Greek words "*lysis*" and "*metron*", which mean dissolving and measuring, respectively. The term is thus applicable to any device utilized for studying the rate, amount, and composition of percolation water through a porous medium. Many definitions of lysimeter are available in the literature. In essence, a lysimeter can be defined as a large container filled with soil, which is located in the field (to represent the field condition) with bare or vegetative surfaces, but isolated from the surrounding field-soil hydrologically, permitting determination of any term of the hydrologic equation (e.g., evapotranspiration, percolation, etc.) when the others are known.

Types of lysimeters

Different types of lysimeters have been developed throughout the world, and various technical solutions have been applied to improve the measurement of evapotranspiration or other components of hydrologic cycle. Lysimeters can be grouped into two main categories:

(a) Weighing lysimeter
(b) Nonweighing or drainage lysimeter

The weighing lysimeters have various weighing principles and devices. They may be based on weighing with varieties of scales and balances or on electronic weighing with strain gauge load cells, or a combination of both mechanical and electronic devices, or on hydraulic weighing systems. A precision weighing lysimeter may be sensitive to 0.03–0.05 mm of water. Short term (10 min or hourly) evapotranspiration can be measured with this type of lysimeter.

The nonweighing lysimeters are also called "volumetric" or "drainage" or "compensation" lysimeters. The water supply may be from natural rain or irrigation or artificially maintained water table or from a combination of these.

Weighing lysimeters based on hydraulic weighing system may be of two types: one is "hydraulic lysimeter", in which the lysimeter weight changes are measured from changes in hydraulic load cells pressure; the other is "floating lysimeter", in which the lysimeter weight changes are measured from changes in buoyancy or floatation.

Purpose of lysimeter

In addition to measurement of ET, lysimeters can be used for the following purposes:

1. To study groundwater recharge patterns and rates
2. To estimate capillary upward flux from different depths of the water-table
3. To estimate the magnitude and pattern of groundwater pollution from agro-chemicals and other wastes
4. To study solute transport patterns and rates
5. To screen drought, water-logging, and salt-tolerant crop cultivars

Choice of lysimeter

A drainage lysimeter with a constant groundwater table may be selected for areas having a shallow water table in the field. For irrigation planning, project design, operation, as well as on-farm water management, high precision lysimeters and hourly ET values are not essential. Reliable monthly and weekly figures are sufficient in most cases. Daily values may be useful in specific cases such as computerized drip and automatic sprinkler systems.

Operation and measurement procedure

Undisturbed monoliths are naturally more representative of field conditions, and as such should be preferred material to fill in a lysimeter,, especially for well-aggregated and stratified soils. But for a large monolith (e.g., $\sim\geq 20$ ton), this becomes a major undertaking. However, for small lysimeters, the process of isolating and enclosing an undisturbed soil block is less troublesome. When filling with disturbed soil, soil layers (with thickness) should be symmetrical with those of the surrounding field soil. In addition, several crop seasons ($2 \sim 3$) should be allowed for settlement of the soil strata through normal crop culture. For ET values, reliable data can be obtained from properly filled-in lysimeters, as long as soil disturbance does not significantly affect plant growth.

For nonweighing lysimeters, water application to the lysimeter surface and buffer area should be provided whenever the soil moisture depletion or tension of the top soil layers reaches a certain level. Although daily observations of drainage, soil water content, etc. can be made, water balance and evapotranspiration values are normally calculated on a weekly or 10-day basis.

The evapotranspiration of a crop can be measured using weighing lysimeters, from the difference in weights between two time periods. It can also be derived from field plot (specially designed, experimental plot) data using the water balance equation at the plot level.

Periodic, thorough water application to the surface of the lysimeter is preferable to produce drainage. Water balance and ET values can be calculated for periods between successive drainage occurrences.

Limitations of lysimeter

Lysimeters are expensive to construct and not transportable. It may not be possible to maintain exact field condition of soil environment, thus the output results. In addition, advection of heat from the surrounding side wall may affect the ET result.

Precautions

Care should be taken so that the soil condition within the lysimeter resembles the field condition. To minimize heat advection, the lysimeter should be placed in the middle of the crop field, and the top edges should be below the soil surface (about 1 ft).

Details regarding lysimeter design and installation can be found in Aboukhaled and Smith (1982) and Hassan et al. (1995).

7.2.1.3 Indirect Estimation of ET

Crop water use is influenced by the dynamics of the soil–plant–atmosphere system. In this continuum, water availability is implicit as the most significant limiting factor for growth and final yield. Because of the diversity of physiological, anatomical, and aerodynamic characteristics, different crops have different abilities to use water. It is difficult to evaluate the water needs of each crop individually. In this context, a reference crop evapotranspiration (ET_0) concept has been idealized by which the ET of other crops is computed through a conversion factor called crop coefficient. This is known as the two-step approach to determine crop evapotranspiration (ET_c), given as follows:

$$\mathrm{ET}_\mathrm{c} = K_\mathrm{c} \times \mathrm{ET}_0, \tag{7.11}$$

where ET_c is the evapotranspiration of a particular crop for a particular period (mm), K_c is the crop coefficient of the respective crop for the crop period (growth stage) concerned, and ET_0 is the reference evapotranspiration (mm).

Adjusting for soil moisture, the ET_c becomes:

$$\mathrm{ET}_\mathrm{c} = K_\mathrm{c} \times K_\mathrm{s} \times \mathrm{ET}_0, \tag{7.12}$$

where K_s is a coefficient that depends upon available soil moisture.

The value of the crop coefficient (K_c) may be obtained from the literature, or may be determined independently from field experimental data of evapotranspiration. The reference evapotranspiration may be computed from local climatic data, using various methods (described later) and tools.

The reference evapotranspiration (ET_0), as defined by FAO-1992 (Smith et al. 1992), is the rate of evapotranspiration from a hypothetic crop with an assumed crop height (12 cm) and a fixed canopy resistance (70 s m^{-1}) and albedo (0.23), which would closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, the green grass actively growing, completely shading the ground and having adequate water.

Estimation of ET_0

Models for predicting ET_0 range from deterministically-based combined energy balance-vapor transfer approaches to empirical relationships based on climatological variables, or to evaporation from a standard evaporation pan. Updated procedures for calculating ET_0 were established by FAO. According to FAO-1992 (Smith et al. 1992), the Penman-Monteith method gives more consistent ET_0 estimates and has been shown to perform better than other ET_0 methods when compared with lysimeter data. The P–M method takes into account almost all the factors that are known to influence ET_0, such as temperature, humidity, sunshine hour, and wind speed. But these weather variables are not available at different locations throughout the world, particularly in developing countries. Air temperature is available at most of the weather stations worldwide while the remaining variables are only collected at relatively few locations, and those recordings are not always very reliable. This lack of reliable weather data lead to the suggestion of using simpler ET_0 estimation equations, and comparing and calibrating the same with standard P–M equation. A relationship of other methods (which requires limited data) with P–M method will facilitate increasing the accuracy of those methods.

The FAO-suggested methods (Smith et al. 1992) for estimating ET_0 are described below:

FAO Penman–Monteith Equation

The Penman–Monteith (P–M) equation is expressed in the form:

$$\mathrm{ET}_0 = \frac{0.0864}{\lambda} . \frac{\Delta(R_\mathrm{n} - G) + c_\mathrm{p}\rho_\mathrm{a}\mathrm{DPV}/r_\mathrm{a}}{\Delta + \gamma(1 + r_\mathrm{c}/r_\mathrm{a})}, \tag{7.13}$$

where λ is the latent heat of vaporization (MJ kg^{-1}); Δ, the slope of the vapor pressure vs. temperature curve ($\mathrm{kPa}°\mathrm{C}^{-1}$); γ, the psychrometric constant ($\mathrm{kPa}°\mathrm{C}^{-1}$); R_n, the net radiation (Wm^{-2}); G, the soil heat flux (Wm^{-2}); c_p, the specific heat of air (1,013 $\mathrm{Jkg}^{-1}\ \mathrm{C}^{-1}$); ρ_a, the atmospheric density (kgm^{-3}); DPV, the vapor pressure deficit ($\mathrm{kP_a}$); r_a, the aerodynamic resistance (sm^{-1}); r_c, the bulk canopy resistance (sm^{-1}); and $0.0864/\lambda$, *the ratio* used to transform Wm^{-2} to mm per day.

FAO Temperature (Blaney–Criddle) Method

The recommended relationship is expressed as:

$$\mathrm{ET}_0 = \mathrm{c}[p(0.46T + 8)], \tag{7.14}$$

Table 7.1 Values of monthly percentage of total annual daytime hours for different latitudes

Month	p for latitude – north (degree)					p *for* latitude – south (degree)				
	15°	25°	35°	45°	60°	15°	25°	35°	45°	60°
Jan	7.94	7.53	7.03	6.38	4.58	9.05	9.46	9.95	10.61	12.40
Feb	7.36	7.13	6.86	6.50	5.59	7.98	8.21	8.49	8.84	9.75
Mar	8.43	8.39	8.33	8.27	8.10	8.55	8.60	8.65	8.72	8.89
Apr	8.45	8.63	8.84	9.10	9.77	7.98	7.81	7.60	7.34	6.67
May	8.99	9.36	9.80	10.38	11.93	8.00	7.63	7.19	6.61	5.06
Jun	8.82	9.27	9.80	10.52	12.56	7.62	7.17	6.63	5.92	3.87
Jul	9.05	9.47	9.97	10.64	12.47	7.93	7.51	7.01	6.35	4.52
Aug	8.84	9.09	9.40	9.79	10.79	8.15	7.89	7.59	7.20	6.19
Sep	8.27	8.30	8.35	8.40	8.54	8.17	8.13	8.09	8.04	7.90
Oct	8.24	8.05	7.83	7.54	6.83	8.75	8.93	9.15	9.44	10.16
Nov	7.73	7.37	6.94	6.37	4.85	8.70	9.07	9.50	10.07	11.59

where ET_0 is the reference crop evapotranspiration (mm/day), T is the mean daily temperature (°C), p is the daily percentage of total annual daytime hours, and c is the adjustment factor.

For calculation of monthly ET_0 value, monthly percentage of total annual daytime hours should be used instead of daily percentage.

The daily day-time hours can be obtained from solar equations. The monthly p values for different latitudes are given in Table 7.1.

FAO Radiation Method

The relationship recommended is expressed as:

$$\mathrm{ET}_0 = c(W\,R_\mathrm{s}), \tag{7.15}$$

where ET_0 is the reference crop evapotranspiration (mm/day), R_s is the solar radiation in equivalent evaporation (mm/day), W is the weighing factor that depends on temperature and altitude, and c is the adjustment factor.

In areas where the measured value of R_s is not available, it can be obtained from measured sunshine duration record with the following equation:

$$R_\mathrm{s} = (0.25 + 0.50\ n/N)R_\mathrm{a}, \tag{7.16}$$

where n/N is the ratio between actual measured bright sunshine hours and maximum possible sunshine hours, and R_a is the extra-terrestrial radiation, which is the amount of radiation received at the top of the atmosphere. Procedure for calculating R_a has been described in Chap. 3 (Weather).

To convert the units from $\mathrm{MJm}^{-2}\mathrm{d}^{-1}$ to mm/day, multiply by 0.408.

The weight factor W depends on daily average temperature and altitude and ranges from 0.5 (low temperature and zero altitude) to 0.9 (high temperature and high altitude) [Doorenbos and Pruitt (1977)]. The adjustment factor C depends greatly on mean relative humidity and daytime wind at 2-m height above the soil surface. Its value generally ranges from 0.75 (high RH and low wind speed) to 1.25 (low RH and high wind speed). Its relation has been shown graphically by Doorenbos and Pruitt (1977). The value of C for a particular location can be obtained by comparing the value of radiation term (WRs) with the FAO Penman-Monteith estimates of ET_0 (Ali et al. 2005).

Hargreaves and Samani Method

Hargreaves and Samani (1985) suggested a method involving only temperature and radiation data. Their equation is given by:

$$\mathrm{ET}_0 = (0.0023R_\mathrm{a})(T_\mathrm{mean} + 17.8)TD^{0.5}, \tag{7.17}$$

where R_a is extra-terrestrial radiation in equivalent mm of water evaporation for the period, T_mean is the mean temperature in °C, and TD is the difference between maximum and minimum temperatures.

Manual calculation of ET_0 is tedious. Computer facility makes it easier to calculate. Recently, different software tools are readily available to calculate ET_0 with easiness.

Pan evaporation Method:

Reference crop evapotranspiration (ET_0) can be obtained from:

$$\mathrm{ET}_0 = K_\mathrm{p}\, E_\mathrm{pan}, \tag{7.18}$$

where E_pan is the pan evaporation in mm/day, and K_p is the adjustment factor.

Determination of Crop Coefficient (K_c)

Crop coefficient (K_c) is defined as the ratio of the actual evapotranspiration of a disease free crop grown in a large field adequately supplied with water to the reference evapotranspiration. In essence, the crop coefficient is a coefficient expressing the difference in evapotranspiration between the cropped and reference grass surface. The difference can be combined into one single coefficient, or it can be splitted into two factors describing separately the differences in evaporation and transpiration between both surfaces.

Single Crop Coefficient

As the single K_c averages soil evaporation and transpiration, the approach is used to compute ET_c for weekly or longer time period, although calculations may proceed on a daily time step. According to the single crop coefficient method,

$$K_c = \frac{\mathrm{ET_{crop}}}{\mathrm{ET_0}}, \tag{7.19}$$

where $\mathrm{ET_{crop}}$ and $\mathrm{ET_0}$ are the crop evapotranspiration and reference crop evapotranspiration at various growth stages, respectively. The K_c includes the effect of evaporation from both plant and soil surfaces.

To determine/establish crop coefficient for a particular crop from field data, field experiment should be designed with treatments providing sufficient water supply (no deficit). For different growth stages (or other forms of expression of growth indicators), the evapotranspiration of the crop ($\mathrm{ET_{crop}}$) should be calculated from water balance equation, as described earlier.

The K_c may be derived from well watered crop as well as from water deficit crop (Ali et al. 2007). This is because, when soil moisture becomes limiting (stress condition), the ratio of ET to $\mathrm{ET_0}$ decreases, and hence the K_c changes from that of the well watered condition.

Alternatively, K_c may be corrected for deficit condition from the well watered K_c as:

$$K_{cc} = K_c\, K_s, \tag{7.20}$$

where K_s is a coefficient depended upon available soil moisture.

Dual Crop Coefficient

In this approach, K_c is splitted into two coefficients: one is for crop transpiration, termed as basal crop coefficient (K_{cb}), and the other is for soil evaporation (K_e). That is,

$$K_c = K_{cb} + K_e. \tag{7.21}$$

The dual crop coefficient approach requires more numerical calculation than the procedure used in single time-averaged K_c. The dual procedure is best for real time irrigation scheduling and soil water balance computations where effects of day-to-day variations in soil surface wetness and the resulting impacts on daily $\mathrm{ET_c}$, the soil water profile, and deep percolation fluxes are important. The examples are high frequency irrigation with micro-irrigation systems or lateral move systems such as centre pivots and linear move systems. The single crop coefficient method is much simpler and more convenient than the dual crop coefficient method and is still well used in practice.

Factors Affecting K_c

Devitt et al. (1992) found that crop coefficients varied between high management and low management systems. Jagtap and Jones (1989) reported that seasonal errors in computing evapotranspiration for soybean could be as high as 190 mm when the crop coefficient developed under one set of conditions were used under different climate and management condition. The K_c also varies with the frequency of precipitation or irrigation. Following emergence, transpiration is limited and soil evaporation constitutes the major part of ET, especially following an irrigation or rainfall. As the percent of ground cover increases, transpiration becomes a large portion of ET. Therefore, changes in irrigation practices are likely to have major impact on the sensitivity of ET and the crop coefficient. Doorenbos and Pruitt (1977) found as much as 70–80% variation in crop coefficient because of differential irrigation during the early phase of crop development.

Since K_c and ET_0 are related through (7.19) for a site, K_c will vary depending on the method used to predict it. Therefore, K_c must be developed for a specific method of computing ET_0, and they can not reliably be used when ET_0 is computed with other methods.

In summary, the K_c depends on the following factors:

- Crop and cultivar type
- Growth stage or phase of the crop
- Percent ground coverage by the crop
- Management system (low or high management)
- Local climatic condition
- Length of growing season or individual growth stage
- Frequency of rainfall or irrigation
- Irrigation history in the early phase of development
- Method of computing ET_0

For the influence of various factors on K_c, crop coefficients need to be developed at each agro-climatic zone because of the different local factors (such as length of growing season, climate, cultivars/hybrids, etc.) that affect the coefficient. The crop growth phase-wise crop coefficient is an important parameter for estimation of consumptive water use of a crop.

Expression of K_c

Crop coefficient may be expressed in several ways:

1. K_c vs. time
2. K_c vs. growth stage
3. K_c vs. percent growing time
4. K_c vs. percent effective cover
5. K_c vs. heat unit
6. K_c vs. LAI

Other than the growth-stage basis expression, the above expressions can be translated into mathematical functional form (Fig. 7.2). Mathematical functional form of K_c is a demand for numerical simulation model. Thus, expression with days

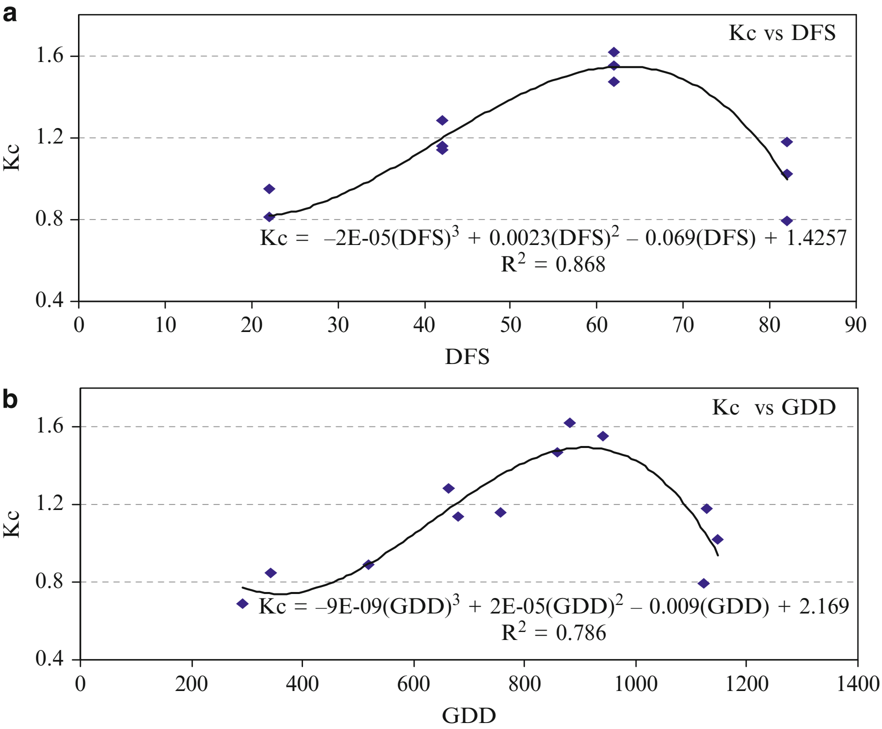

Fig. 7.2 Crop coefficient of winter wheat (120 days duration) as a function of (**a**) days from sowing, and (**b**) heat unit (GDD, degree-days) (after Ali 2008)

(time), percent growing time, percent effective cover, heat unit, and LAI facilitate such uses.

K_c vs. Time

The distribution of the crop coefficients for a particular crop as a function of time constitutes a crop curve. Crop curves can be expressed as K_c vs. time, where time can be a Julian date or days since sowing or planting (DFS or DFP).

K_c vs. Percent Effective Cover

Crop curves may be expressed as a function of percent effective cover from 0 to 100, and then days after effective cover.

K_c vs. Heat Unit, K_c vs. LAI

Crop coefficient may also be presented as a function of heat unit, such as growing-degree-days (GDD) after planting or emergence, or as a function of a LAI. Relating crop coefficients to GDD is superior to relating crop coefficients to Jullian date or percent time, or elapsed days. The method of determining heat unit has been described in Chap. 3 (Weather and Climate).

K_c *vs. Growth Stage*

Crop curves can also be expressed as a function of growth stage, where the crop coefficient may be constant or linearly increasing over that stage. The crop growth periods are divided into stages, and the number of days at each stage is then specified. Doorenbos and Pruitt (1977) divided the K_c curve into four stages: initial, crop development, mid-season, and late-season stages. The change in the slope of the curve reflects a change in the stage (Fig. 7.3).

Other Empirical Formula for Estimating Evapotranspiration

Makkink's formula: Makkink (1957) suggested an empirical relation for estimating ET based on solar radiation measurements weighted according to air temperature:

$$\mathrm{ET} = 0.61Q\frac{\Delta}{\Delta + \gamma} - 0.12, \tag{7.22}$$

where Q is the incoming radiation expressed in mm/day (converted into the amount of water evaporated), Δ is the slope of the saturated vapor pressure–temperature curve at

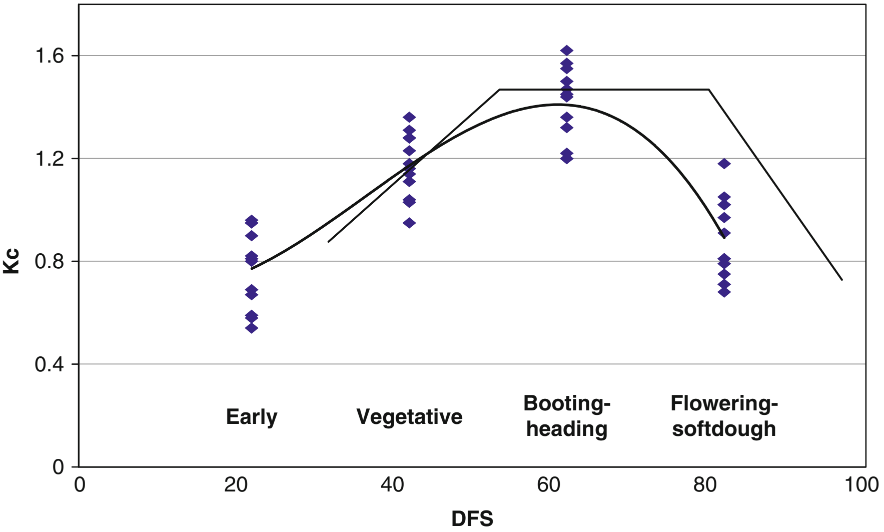

Fig. 7.3 K_c of wheat vs. growth stage (after Ali 2008)

the mean temperature, and γ is the psychrometric constant (0.49°C and mm of mercury, or 0.27°F and mm of mercury).

Potential Evapotranspiration

It is the maximum possible evapotranspiration of a crop during a particular growth period. It is used in irrigation and drainage project design, and planning purposes, and also in command area estimation.

7.2.2 Evaporation

7.2.2.1 Concept and Importance of Evaporation

Evaporation is the process by which molecules in a liquid state are transformed into a gaseous state. Whenever water (or even ice and snow) is exposed to air, it evaporates (i.e., transfers into gaseous state) and mixes with the gases in the air. The atmosphere as a whole never saturated with water vapor, but may be at local scale. The rate of evaporation is defined as the amount of water evaporated from a unit surface area per unit time. It is expressed in different units: mass/unit area/unit time ($M\ A^{-1}\ T^{-1}$), volume/unit area/unit time ($V\ A^{-1}\ T^{-1}$), and depth/unit area/unit time ($D\ A^{-1}\ T^{-1}$). Unit area is usually considered one square meter (1 m^2), and the unit time is considered "day" (d).

The direct evaporation of water from the surface of the soil often involves considerable water losses in dryland and irrigated farming. Under field crops the soil may remain bare for many weeks at the very early stage (e.g., seed germination and seedling establishment) when the water content at the upper soil layer can be of great importance. It can also be of important for subsequent growth stages. In addition, evaporation data are required in hydrological studies, such as estimation of water yield in an area, planning and design of water resources projects, rainfall-runoff modeling, water balance studies, etc.

Evaporation of soil-water involves not only the loss of water but also the danger of soil salinization. This threat is serious in regions where the fresh irrigation water is limited and annual rainfall is low, as well as in areas with a high saline groundwater table.

Sandy soils and soils with saline groundwater occupy large areas of the world and are most extensive in semi-arid and arid regions. The water content of the top layer of a soil profile greatly influences how efficiently precipitation and irrigation water are used for crop production. Thus, evaporation from bare soils plays an important role in irrigation water management and land-use problems. For maximum efficiency, conservation of water in the soil profile may be achieved either by reducing evaporation from the soil surface or by improving the physical properties of the top soil, or both.

7.2.2.2 Evaporation Process

Evaporation from Free Water Surface

Evaporation is an energy-dependent process. The water molecules are attracted themselves by cohesive force (inter-molecular force). To evaporate water from a water surface, a higher energy is needed to break this attraction. In addition, energy is also needed to vaporize (heat of vaporization).

The molecules of water at the surface of a water-body receive energy from solar radiation and adjacent air. Because of the temperature rise in the water, the kinetic energy of the molecules increases. This kinetic energy is proportional to the temperature. When the kinetic energy is sufficient enough to overcome the inter-molecular force, the water molecule escapes from the liquid surface (i.e., evaporates).

As the evaporation process continues, the air over the water surface becomes humid, close to saturation (decreases the vapor pressure difference of air and water), and the evaporation rate decreases. As the water vapor is transferred by air turbulence, the process continues. Thus, it can be said that, evaporation rate is controlled by vapor pressure deficit of air.

Evaporation from Soil Surface

Evaporation of water from a thoroughly wetted soil may be characterized by three stages:

1. A first or constant stage: when the soil surface is wet with water moving primarily in the liquid phase, and evaporation is controlled by external condition.
2. A second stage of short duration and of rapidly decreasing evaporation rate: this begins when dry surface soil first appears.
3. A third stage of slow evaporation rate: where water movement through the dry surface is mainly by vapor diffusion, and evaporation is controlled by internal conditions.

7.2.2.3 Factors Influencing Evaporation

Evaporation from Free Water Body

Evaporation from free water surface is influenced by the following:

- Available energy
- Humidity of the adjacent air
- Temperature of the air
- Air movement/wind flow
- Purities/impurities of water
- Pressure over the water surface

Available Energy

Energy is needed to initiate and continue the evaporation process. When the energy increases (as solar energy or advective energy), the evaporation rate increases, subject to other factors does not change, or change in the positive direction.

Humidity (Actual and Relative) of Adjacent Air

During evaporation process, the escaped water molecules (i.e., the water vapor) are accumulated in the air above the water surface. As a result, the vapor pressure difference of water and adjacent air becomes the driving force of water evaporation (the rate of water movement is everywhere proportional to the potential gradient and inversely proportional to the resistance to flow). Under a low relative humidity, evaporation goes on rapidly, and vice versa. If the air is saturated (relative humidity is equal to 100%) or near saturated, no more water will evaporate.

Temperature of the Air

The amount of water necessary to saturate air varies greatly with the temperature. As the air temperature increases, the vapor holding capacity of the air increases (resulting increase in vapor pressure deficit of the air), which ultimately increases the rate of evaporation.

Flow of Air Above the Water Surface

The replacement of saturated air by drier air from over the water surface depends on the air movement or wind speed. Hence, the evaporation rate greatly depends on wind speed.

Impurities of Water

If the concentration of water is higher due to existence of salt, clay or other impurities/substances, more energy will be required to evaporate, thus lower the rate of evaporation.

Pressure over the Surface

If the pressure over the water surface is lower, evaporation will be faster because there is less exertion of force on the surface keeping the molecules from launching themselves.

Evaporation from Soil Surface/Crop Field

In addition to the factors mentioned above, factors influencing evaporation from soil surface and/or crop field are as follows:

- Degree of soil saturation/amount of soil water
- Type of soil
- Percent shading
- Rate of drying
- Tillage or mulching
- Depth of tillage

Amount of Soil Water

The evaporation rate is directly related to the moisture supplying capacity of the soil at the soil surface. Upward capillary flow of water from shallow water table or deeper soil layer may provide such moisture. If the soil is able to supply water at a rate equal to or greater than the atmospheric evaporative demand, the evaporation rate is determined by the meteorological conditions. However, at lower soil moisture, the film around the soil particle is thinner, and thus the adhesive force with the soil particle is increased. As a result, more energy is needed to break this bond. Thus the evaporation rate decreases with the decrease of soil moisture.

Type of Soil

Type of the soil has a role in water movement, and thus on water availability for evaporation. In coarse-textured soil, the capillary movement of water is lower and the specific heat capacity of the evaporating surface is higher. On the contrary, in fine-textured soil, the capillary movement of water is higher.

Percent Shading/Bare Surface

Evaporation from soil surface in a cropped field depends on the percentage bare surface on which direct solar radiation can reach. Higher percentage of bare surface can also provide advective energy for the shaded area.

Rate of Drying

With the decrease of soil moisture, hydraulic conductivity of soil (for capillary movement) decreases rapidly. If the upper top-soil layer dries rapidly, the supply of water from the deeper layer will be restricted. In the presence of high radiation, a surface soil mulch of dry soil may develop within a few hours after the soil has been irrigated. The dry soil mulch can acts as a capillary break and reduces the evaporation rate. Under low evaporative demand condition (e.g., cloudy condition), the bare saturated soil may provide with continuous flow, and the rate of evaporative loss may approximate that of a free water surface for a longer period, and may lead to greater total loss (due to influence of advective energy).

Tillage or Mulching

Evaporation happens directly from the top layer, and not from the deeper layer. Tillage breaks the pathway of capillary movement from the deeper layer. Similarly, mulch restricts the solar radiation to reach to the soil surface, creates a barrier of heat conductance, and thus reduces the amount of evaporation.

7.2.2.4 Measurement/Estimation of Evaporation from Free Water Surface

Direct Measurement

Measurement of evaporation from free water surface can be done installing a graduated scale or staff gauge. The vertical fall of water level between two consecutive time periods (e.g., t_1–t_2 h) indicates the loss due to evaporation and percolation. Subtracting the percolation component from the total loss, evaporation loss can be obtained. That is,

$$e = \frac{F - P}{t_2 - t_1}, \tag{7.23}$$

where e is the evaporation rate (mm/h), F is the fall in water level (9 mm), t_1 is the starting time (h), and t_2 is the ending time (h).

Percolation rate can be estimated by suppressing the evaporation loss in a small water body by covering with polythene.

Estimation of Evaporation by Empirical Equations

Dalton Equation

Dalton's equation for estimating evaporation from a water surface (E_0) is:

$$E_0 = (e_s - e)f(u), \tag{7.24}$$

where e_s is the vapor pressure at the evaporating surface, e is the vapor pressure at some height above the surface, and $f(u)$ is a function of the horizontal wind velocity.

As the roughness of the water surface does not vary so much, Rohwer (1931) has evaluated the constants in the Dalton equation and suggested as:

$$E_0 = 0.40(e_s - e)(1 + 0.17u_2)\text{mm/day}, \tag{7.25}$$

where u_2 is the wind speed in miles per hour at 2-m height.

Penman Equation

The Penman equation consists of two terms: the energy term and the aerodynamic term. The Penman formula for evaporation from open water surface is (Penman 1948):

$$E_0 = \frac{\Delta Q_n + \gamma E_a}{\Delta + \gamma}, \tag{7.26}$$

where E_0 is the evaporation from open water surface in mm/day; Δ is the slope of the vapor pressure versus temperature curve (de_a/dT) at the air temperature T in millibar per degree Celcius; T is the temperature in degree Kelvin; $Q_n = (1-r)Q_A\ (0.18 + 0.55\ n/N) - \sigma\ T^4\ (0.56 - 0.092\sqrt{e_d})\ (0.10 + 0.90\ n/N)$ is the net radiation expressed in evaporation units; Q_A is the Angot's value; n/N is the ratio between actual and maximum possible sunshine hours; σ is the Stefan– Boltzman constant; e_d is the saturation vapor pressure in mm of mercury at the dew point temperature; γ is the psychrometric constant *or* the ratio of the specific heat of air to the latent heat of evaporation of water; $E_a = 0.35\ (e_d - e_s)\ (0.5 + u_2/100)$ is an aerodynamic component; and u_2 is the wind speed in miles/day at 2-m height.

Penman equation requires data of temperature, radiation, wind speed, and humidity. Manual computation of this formula is complex, but with the aid of computer it can be calculated easily.

Mayer Formula

Evaporation rate (E) from pan, shallow pond, small lake, and reservoir is calculated as (Meyer 1942):

$$E = (15 + 0.93W)(e_s - e_d), \tag{7.27}$$

where E is the evaporation (mm/month), W is the average wind speed for the month in km/h at a height of 7.6 m, e_s is the saturated vapor pressure of the air in mm of Hg, and e_d is the actual vapor pressure of the air in mm of Hg. The difference ($e_s - e_d$) is the vapor pressure deficit.

Rohwer Formula

Daily evaporation from free water surface is given by (Rohwer 1931):

$$E = (0.44 + 0.073W)(1.465 - 0.0073P)(e_s - e_d), \tag{7.28}$$

where E is the evaporation (mm/day), W is the average wind speed for the month in km/h at a height of 0.15 m, and P is the atmospheric pressure in mm of Hg at 0°C.

Measurement of Evaporation by Evaporation Pan

The evaporation pan *or* evaporimeter incorporates the effects of all weather variables (since it is installed in open field), and hence it is more accurate in estimating evaporation from large water bodies *or* estimating short-term fluctuation of evapotranspiration than empirical formulae that depend on fewer of the weather factors involved. Evaporimeters are easy to make, inexpensive, and easy to handle in the field. It is the most satisfactory device for field use.

Various types of evaporation pans are available in practice throughout the world. The USWB Class-A pan is the standard evaporimeter internationally. Among other types of evaporimeter, Australian standard pan, sunken pan, etc. are prominent.

The rate of evaporation from a pan varies with its size, color, material, the height at which the evaporation pan is installed, height of the pan, depth to water surface from the top, exposure, position (whether at the crop field *or* at an un-cropped field), etc. Because of the difference in reflectivity, the black pan may lose up to 20% more water than the white pan. A steel or copper pan may lose about 10% more than an aluminum pan. The water level in the pan also influences the water loss mainly caused by air flow and the disturbing effect of the pan wall, and the excessive heating of the upper part of the pan wall. To eliminate the effects of pan size, color, exposure, and other design parameters, the World Meteorological Organization has adopted the United States Weather Bureau (USWB) Class A pan as the standard pan evaporimeter.

Description and Operation of USWB Class-A Pan Evaporimeter

The US Weather Bureau Class A pan is made of galvanized iron. It is cylindrical in design (Fig. 7.4) having 1,207 mm in diameter (inside dimension) and 254-mm height. The thickness of the pan is 0.8 mm (22 gauge). The pan is placed on a wooden platform having air circulation facility beneath the pan. The platform should be leveled and bottom of the pan should be approximately 10 cm above the ground. A perforated stilling well (a 4~5-cm diameter metal tube having a small hole at the middle or bottom, and having good support at the bottom),

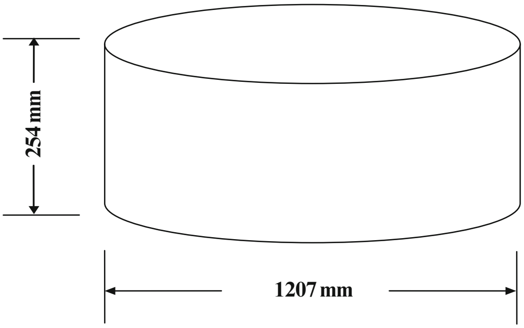

Fig. 7.4 Sketch of a USWB Class A Pan

normally a little shorter than the depth of pan, is installed within a side of the pan to take the water level data within the well. This is done to avoid the turbulence of the wave (caused by air flow) during observation.

The installation site should be free from obstacles so that air flow and solar radiation are not obstructed. The pan should be filled to a level of 5 cm below the top of the pan, and refilled when the water level drops by about 2~3 cm from the initial reference level.

Measurement of Evaporation in USWB Pan

Pan reading should be taken at a particular fixed time of the day (preferably early in the morning, typically at 9:00 AM). Depth of evaporation between two successive measurements is equal to the difference in depth of water. Measurement of water level can be accomplished by a linear scale (feet or meter scale) or a hook gage coupled with a vernier scale. For accurate reading of the scale *or* exact matching of the hook gauge to water level, it is advisable to use a magnifying glass (enlarger of the views). The difference in the readings for the current day and the previous day represents the pan evaporation of the previous day. To avoid any error, cumulative difference in reading may be recorded in addition to daily evaporation calculation.

Pan Coefficient

The evaporation from the pan is normally higher than the large water bodies because of the higher advective energy available in case of the pan. The evaporation from large water bodies (E_{w}) is obtained as:

$$E_{\mathrm{w}} = E_{\mathrm{pan}} \times K_{\mathrm{p}}, \tag{7.29}$$

where E_{pan} is the pan evaporation, and K_{p} is the pan coefficient.

Thus, the pan coefficient is obtained as:

$$K_{\mathrm{p}} = \frac{E_{\mathrm{w}}}{E_{\mathrm{pan}}}.$$

The average value of K_p is about 0.7.

Relation Between Evapotranspiration and Pan Evaporation

It is possible to develop relationship between evapotranspiration and pan evaporation. The life cycle of the crop may be divided into several well-defined stages, and such a relationship (or ratio) can be developed for each stage, and in each agro-climatic region. The relation can then be used for estimating crop water requirement from pan evaporation data.

Pan evaporation is related to reference evapotranspiration as:

$$\mathrm{ET}_0 = K \times E_{\mathrm{pan}}, \tag{7.30}$$

where K is a coefficient relating pan evaporation to reference evapotranspiration.

7.2.2.5 Evaporation from Bare Soil and Crop Field

Bare Soil

Evaporation from bare soil may take place at the same rate as evaporation from a free water surface until a certain critical deficit of moisture content is reached (upto ~20–30% drop of available moisture). If the ground is kept wet all the time, evaporation from bare soil may exceed the free water evaporation due to higher specific heat capacity. But in practice, it is not possible to keep the soil wet at all the time by applying irrigation continuously.

Cropped Soil

Evaporation from cropped soil may be estimated using the method of Cooper et al. (1983):

$$E_{\mathrm{c}} = E_{\mathrm{f}}(1 - i), \tag{7.31}$$

where E_{c} is the evaporation from cropped soil, E_{f} is the evaporation from fellow soil, and i is the proportion of radiation intercepted by the crop.

Radiation interception by the crop should be recorded continuously using a special solarimeter (e.g., Delta-T tube solarimeter). It should be placed close to the soil surface across several rows and the integrated reading should be recorded weekly. One solarimeter should be placed above the crop canopies to measure the incident radiation so that the fraction of incident radiation intercepted by the canopy could be calculated.

7.2.2.6 Effect of Salinity on Evaporation

Morton (1986) developed a method for adjusting evaporation rate on the basis of water salinity:

$$E = \frac{E_{\mathrm{fw}}}{1 + \frac{S_{\mathrm{c}}}{10^6}}, \tag{7.32}$$

where E is the lake evaporation under saline condition (mm), E_{fw} is the lake evaporation under fresh water (mm), and S_{c} is the salinity level (ppm).

The salinity is often measured in EC units (e.g., dS/m or μS/cm). The conversion from EC to a concentration of dissolved solids depends on the ionic composition of the water. For water where unusual ionic composition is not expected, it is common to assume that the concentration of total dissolved solids,

$$\begin{aligned} TDS(\text{ppm or mg/L}) &= 640 \times EC(\text{dS/m}) \quad \text{for } EC < 5\text{dS/m} \\ &= 800 \times EC(\text{dS/m}) \quad \text{for } EC > 5\text{dS/m} \end{aligned}$$

7.2.3 Surface Runoff

The amount of runoff generally is small in agricultural fields and particularly in irrigated fields. So, it can sometimes be regarded as negligible in comparison with the major components of the water balance. If runoff occurs it should be quantified. Surface runoff can be avoided by making high levees. However, when there is heavy rain then surface runoff occurs. In that case, surface runoff may be deduced indirectly from total rainfall as:

$$\text{Effective rainfall} = \text{Total rainfall} - \text{Surface runoff}$$

or

$$\text{Surface runoff} = \text{Total rainfall} - \text{Effective rainfall.}$$

Here, surface runoff will depend on the bund height *or* height of the levee of the field plot, depth of water in the plot before rainfall, and the amount of rainfall.

For crop fields having high levees, the surface runoff can be calculated as:

$$\begin{aligned} \text{Surface runoff} = {} & \text{Total rainfall} \\ & - (\text{Height of levee} - \text{height of water in the field before rainfall}) \end{aligned}$$

Procedure for calculating effective rainfall for irrigation scheduling has been described in detail in Chap. 9 (Crop Water Requirement and Irrigation Scheduling). Procedure for estimating peak surface runoff (runoff volume) from a watershed due to rainfall has been described in Chapter: Land and Watershed Management, Volume-2.

7.2.4 Deep Percolation or Deep Drainage

7.2.4.1 Concept

The general trend of water is to move downward (toward horizontal hydraulic gradient and vertical direction) until it reaches the water-table. Percolation is the downward flow of water through soil and porous medium (fractured rock, stone, etc.). The unit of percolation is the same as that of velocity. Normally it is expressed as depth per day (mm/day, m/day, etc.).

7.2.4.2 Factors Affecting Deep Percolation

Deep percolation or deep drainage is influenced primarily by soil, rainfall/irrigation, land use, subsurface condition, and management factors. The specific factors include the following:

- Soil type (texture)
- Structure
- Sizes of pore
- Topography
- Soil management
- Surface cover
- Cropping pattern or rotation
- Crop root zone depth
- Rainfall pattern or irrigation type (sprinkler, drip irrigation emitters, etc.) and amount
- Stream size
- Frequency of irrigation *or* intensity and temporal distribution of rainfall
- Opportunity time for infiltration and/or percolation
- Atmospheric evaporative demand
- Subsoil hydraulic conductivity
- Presence of plow pan or hard layer below the surface layer
- Depth to ground-water level

Deep percolation can be extremely variable within one soil type and within one field, and irrigation with saline water and gypsum application can increase deep drainage. In cracking soil, the initial rate of percolation is high unless the cracks (which are formed due to dryness) are filled up by swelling the soil.

There is a need for a systematic and comprehensive approach to understand deep drainage for a range of soil types, land uses, and management practices.

7.2.4.3 Determination of Deep Percolation

Different methods or approaches are available to estimate deep drainage:

(a) Field-plot water balance
(b) Drainage lysimeter
(c) Darcian flux calculation
(d) Chloride mass balance
(e) Groundwater table rise

From Field-Plot Water Balance

Deep percolation can be estimated as the difference between water added to the system (net irrigation and rainfall) and evapotranspiration. The principle in this method is that the water loss from a crop field takes place as evapotranspiration, surface runoff, and seepage and percolation. That is,

$$D = R + I - SD - \Delta S - \mathrm{ET_c}, \tag{7.33}$$

where D is the deep drainage, R is rainfall, SD is surface drainage, ΔS is the change in soil water storage, and $\mathrm{ET_c}$ is the crop evapotranspiration.

For ponded condition (particularly rice field), if no water is added to or drained out from the field, then the total water use would be due to ET and seepage & percolation, and would be reflected by a corresponding subsidence or loss of head of water on the field surface.

Assuming that daily evapo-transpiration is computed from weather data or pan evaporation data and subtracted from this head loss (fall in depth of water), the remainder of the daily fall in water level is equal to the seepage and percolation. Seepage can be controlled by providing buffer zone around the experimental field plot and maintaining water depth in the buffer zone as that of the experimental plot.

For measurement of fall of water level, inclined meter sticks at a specified slope (e.g., 5:1) may be placed in the field supported with wooden frame. This inclination provides magnification of fall in water depth. Water level on the inclined meter scale may be recorded everyday at 9 AM. For example, the meter scale is inclined at a slope of z:1. The percolation rate is computed as:

$$P = \frac{WD_{\mathrm{i}} - WD_{\mathrm{f}}}{N \times z} - ET_{\mathrm{t}}, \tag{7.34}$$

where P is the percolation (mm/day), WD_{i} is the water depth on the meter stick at the start of the measurement (initial depth) (mm), WD_{f} is the water depth on the meter stick at the end of the measurement (final depth) (mm), $\mathrm{ET_t}$ is the evapo-transpiration per day between the measurement periods (mm/day), N is the number of days between the two measurements (d), and z is the slope of the meter stick.

If the meter stick is not inclined (i.e., vertical), the value of z is one (1). If there is rainfall between the two measurement periods, the average daily rainfall amount should be subtracted from the above equation.

Water balance technique provides estimate of deep percolation for each individual irrigation. But in areas with heavy rainfall, it may give potentially greater error for the whole year.

By Drainage Lysimeter

Drainage lysimeter, which is resembled to field-soil condition, can be used to estimate deep drainage. Cultural practices in lysimeter should be similar to that of field crop.

Outflow from the bottom of the lysimeter would represent the deep drainage. Dividing the outflow volume by the surface area of the lysimeter, the deep drainage depth can be obtained. The deep drainage can be estimated under natural rainfall condition (for a particular season or year) or under simulated rainfall similar to long-term average rainfall.

The most accurate and direct method for determining all components of the water balance is using lysimeter. However, this must be done and interpreted very carefully to avoid artifacts due to edge effects and provide realistic root zone conditions.

By Darcian Flux Calculation

For this approach, the measurements of soil moisture content and concurrent soil water potential are to be done at different soil depths (e.g., 20–160 cm, at 20-cm interval). Hydraulic conductivity of different layers is also to be determined. Then, deep percolation is estimated according to Darcy's law, multiplying the measured suction gradient by hydraulic conductivity at the ambient water content:

$$q = k\frac{\partial \phi}{\partial y} = ki_{\phi}. \tag{7.35}$$

Deep drainage estimation by Darcian flux calculation for seasonal or yearly basis may be highly variable, and thus the estimates may be unreliable.

For estimation of capillary rise, "capillary conductivity" should be used instead of hydraulic conductivity. For this, capillary conductivity function of the soil layers should be established. The soil layer should be situated well below the deepest roots.

Chloride Mass Balance in Soil

In semi-arid zones, direct measurement of deep drainage is problematic because the errors of measurement are close to the annual drainage rates. Use of naturally occurring chloride in the soil to estimate long-term average deep drainage rate is a useful tool where annual drainage rates are low.

Chloride mass balance (CMB) for a soil profile at steady-state condition may be written as:

$$D \times C_{\mathrm{d}} = I \times C_{\mathrm{i}}, \tag{7.36}$$

where D is the deep drainage at a particular soil depth (mm/month), C_{d} is the chloride concentration of drainage water (pore water below root zone) (mg/liter), I is the infiltration of rain and irrigation water (mm/month), C_{i} is the average chloride concentration of rain and irrigation water (mg/liter).

The key assumptions in this method include: (a) vertical flux of chloride below the root zone, (b) no soil (or other) sources or sink of chloride.

It is a reliable method for estimating deep percolation, but only gave an estimate for the entire growing season.

Water Table Rise

Quantification of natural deep percolation may be assessed from groundwater fluctuation or rise in water level (piezometric level). For a particular time period, the rise in water level (WL) from the original one (position of WL at the start of time considered) represents the rise due to deep percolation for that period. Deep percolation can be obtained by multiplying the water-table rise by specific yield of the formation:

$$D = h \times S_{\mathrm{Y}}, \tag{7.37}$$

where D is the deep percolation for the specific time period (cm), h is the rise in water table (or piezometric surface) (cm), and S_{Y} is the specific yield of the subsurface formation at the water table (%).

Specific yield is calculated as:

$$S_{\mathrm{Y}} = \text{Porosity} - \text{Specificretention.}$$

Specific yield can also be estimated from the difference in water content of the formation materials at saturation and field capacity (after gravity drainage).

This approach is suitable for a seasonal or yearly estimate. Short-term estimate may be associated with error due to time-lag of percolated water to reach the groundwater level.

In many cases, groundwater fluctuations may be influenced by massive but unknown water extraction and do not reflect natural conditions.

7.2.4.4 Typical Deep Percolation Rates

Typical deep percolation rate under ponded condition for different soil types are given below:

Soil type	Deep percolation rate (mm/day)
Sandy	3–8
Loamy	2–4
Clay	1.5–2.5

In humid climate, yearly percolation varies from 6 to 18% of precipitation (~50–200 mm/yr) depending on the various soil types, surface cover, and rainfall pattern. In arid and semi-arid climate, the percolation is too low, almost negligible (<1% of precipitation).

7.2.5 Upward Flux/Capillary Rise from Water-Table

7.2.5.1 Concept and Its Importance

Crops having medium to deep rooted system are capable of extracting significant quantities of water from shallow water-table or saturated soil layer. In the presence of a shallow water-table or saturated layer, the upward water movement by capillary rise from the groundwater to the root zone is an important flux at the bottom boundary of the root zone. Shallow water-table contribution to supply crop water use is important, especially in arid and semi-arid regions. Under arid conditions, the water table can supply as much as 60–70% of a crop's water requirement. Successful use of the water table depends on the soil's water retention and transmission properties, evapotranspiration demand, and distribution of the plant roots systems. In irrigation and drainage design, the effect of high water table on crop growth and drainage system performance should be taken into account.

7.2.5.2 Factors Affecting Upward Flow/Ground-Water Table Contribution

The proportion of crop water use from upward flow is mainly influenced by the following:

- Soil type (texture)
- Water-table depth
- Crop root system and depth of rooting
- Irrigation interval (withheld of irrigation)
- Soil dryness (soil-water depletion below field capacity)
- Evapotranspiration demand
- Salinity of water

Crop water use through capillary upward flow (upflow) decreases with increasing water-table depth and salinity. It also decreases with light-textured (sandy) soil. Capillary upflow increases with longer irrigation interval or where irrigation is withheld, dense & effective root system and soil dryness. It increases with heavy-textured (clay) soil. Khan et al. (1973) reported that with a water table at 7 feet below ground under arid condition, high yield of wheat and cotton were obtained without any subsequent watering after the initial 4-in. irrigation.

7.2.5.3 Estimation of Upward Flux

The main difficulty in solving the water balance equation at the plot level is in estimating the soil-water flux component, which requires a precise knowledge of the profile of soil hydraulic properties. The measurement of root zone or subsoil water content by itself cannot tell us the rate and direction of soil water movement. Even if the water content at a given depth remains constant, we can not conclude that the water there is immobile since it might be moving steadily through that depth.

A transition zone can exist in the soil profile above which there is an upward soil-water flux ($\mathrm{d}H/\mathrm{d}z > 0$) and below which there is a downward flux or drainage ($\mathrm{d}H/\mathrm{d}z < 0$). The transitional zone is termed as zero flux plane ($\mathrm{d}H/\mathrm{d}z = 0$) [Fig. 7.5].

Fluxes and water balances can always be calculated using Darcy's equation, but the existence of a zero flux plane may make it possible to calculate soil-water balances without Darcy's equation. In situations without and with a zero flux plane we may proceed as follows:

In the Absence of a Zero Flux Plane

Under this condition, there is either continuous drainage or continuous upward movement, and flux density is determined by Darcy's equation as:

$$q_z = K(\bar{\theta})\frac{\mathrm{d}H}{\mathrm{d}z}, \tag{7.38}$$

where $K(\bar{\theta})$ is the hydraulic conductivity corresponding to an average soil-water content $\bar{\theta}$ during the period considered, dH is the difference in hydraulic potential, dz is the difference in distance over which the difference in hydraulic potential is measured, dH/dz is the average hydraulic potential gradient or the driving force,

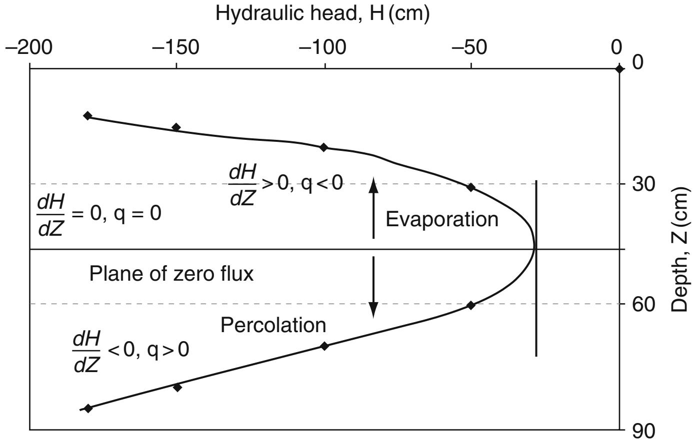

Fig. 7.5 Schematic of zero flux plane in soil layer

where $H = h + z$; h is the matrix potential or soil-water pressure head, and z is the gravitational potential or gravitational head.

In some books, negative sign is imposed in Darcy's equation (in front of K) because the direction of the flux is where the potential decreases. Therefore, upward or downward flux in the profile will depend on the sign of the hydraulic gradient.

In Presence of a Zero Flux Plane

The position of the zero flux plane can be determined from the hydraulic profiles measured by the tensiometers. The average depth of the zero flux plane $\bar{z}_0$ is taken as the arithmetic mean during a particular time period. Upward flux,

$$U = \int_0^{\bar{z}_0} (\theta)\mathrm{d}z. \tag{7.39}$$

Determination of ET by the zero flux plane method is possible for uncropped or cropped soil where the rooting depth does not exceed $\bar{z}_0$. In other cases, (7.33) must be used to determine the flux and ET or evaporation (E).

The drainage flux density at depth z_r can be calculated by either (7.33) or as

$$q_{z_\mathrm{r}} = \frac{\mathrm{d}}{\mathrm{d}t} \int_{\bar{z}_0}^{z_\mathrm{r}} (\theta)\mathrm{d}z. \tag{7.40}$$

Empirical Equations for Estimating Water-Table Contribution

A general form of empirical equation describing groundwater contribution dependence of depth to water-table is:

$$q_\mathrm{u} = G_\mathrm{c}/ET_\mathrm{a} = a - bD, \tag{7.41}$$

where q_u is the ratio of groundwater contribution (G_c) to actual evapotranspiration ($\mathrm{ET_a}$), "a" and "b" are empirical constants that depend on soil type and hydraulic properties, and D is the depth to water table.

Different researchers got different empirical relations for water-table contribution under varying soil, crop, soil dryness (soil-water depletion below field capacity), water-table depth, and environment & management conditions. Some of such equations are cited below (Table 7.2).

[a]Definition of terms of the equations:

No.1, 2: G_c is the groundwater contribution, $\mathrm{ET_a}$ is the actual evapotranspiration, "a" and "b" are empirical constants that depend on soil type, D is the water table depth.

Table 7.2 Empirical equations for estimating capillary rise

Sl no.	Crop	Depth to water table (m)	Equation[a]	R^2 value found	Reference
1	Corn	1–2	$G_c/ET_a = 0.79–0.52D$	0.68	Sepaskhah et al. (2003)
2	Sorghum	1–2	$G_c/ET_a = 1.01–0.57D$	0.58	Sepaskhah et al. (2003)
3			$G = a/\{\exp(10bh)–1\}$		Wenyan et al. (1994)

No. 3: "a", "b" are coefficients of the unsaturated hydraulic conductivity of soil, $K(h)$, cm/day, given in the following eqn: $K(h) = a\exp(-10bh)$, where h is the soil matric potential (MPa).

7.2.5.4 Magnitude of Contribution of Upward Flow

Crop water use through capillary rise or upflow from shallow water tables or saturated zone (0.6–1.3 m) can be significant, upto 25∼40% for maize, wheat, soybeans; and 50∼60% for Lucerne and cotton crop. The proportion of crop water use from upflow varies between soil types, water table depth, salinity of water, and irrigation interval. Crop water use through capillary upflow decreases with increasing water-table depth and salinity, and increases with longer irrigation interval or where irrigation is withheld.

7.2.6 Determination of Change in Soil-Water storage

The change in soil-water storage can be determined by subtracting the final soil-water storage of the time period considered, from the initial soil-water storage (Fig. 7.6). That is,

$$\Delta SM = SM_{\mathrm{i}} - SM_{\mathrm{f}}, \tag{7.42}$$

where ΔSM is the change in soil-water storage (mm), SM_{i} is the total profile soil-water depth at the starting of the time period considered (mm), and SM_{f} is the total profile soil-water depth at the ending of the time period considered (mm).

Soil-moisture storage at a particular period can be measured by sampling periodically (gravimetric determination) or by use of specialized instrument viz., neutron moisture meter, time domain reflectrometer (TDR), diviner, etc. Soil-water content should be measured for different depths at the starting and ending of the time period considered. The procedure for measuring soil moisture has been described in detail in Chap. 3 (Soil).

Procedure for calculating the total profile moisture

For example, soil-water content is measured by neutron moisture meter at depths of 15, 30, 45, 60, 75, and 90 cm. The corresponding moisture contents are 25, 28, 30, 35, 38, 42% (by volume). Now, we have to calculate the total profile moisture.

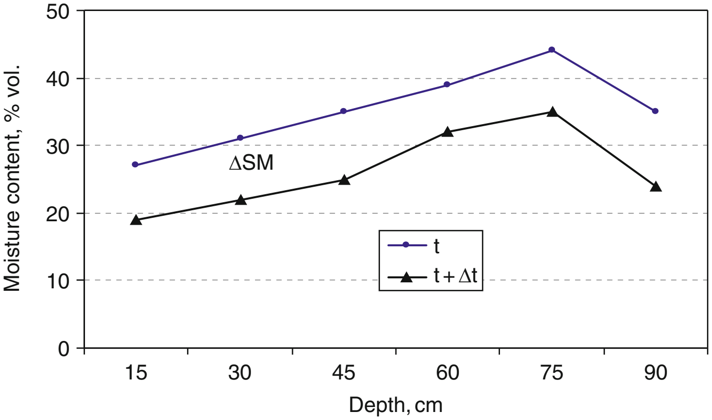

Fig. 7.6 Soil-water content profile at two different times and change in soil-water storage

Step-1: Convert the volumetric moisture to water-depth for each section.

Water-depth (cm) = (volumetric moisture content, in percent)/100 × depth of measured section (in cm)

For this example, the depth of each section is 15 cm ($15-0=15, 30-15=15$, etc.)

Soil depth (cm)	0–15	15–30	30–45	45–60	60–75	75–90
Moisture content (V_i),% vol.	25	28	30	35	38	42
Water-depth (W_i), (cm)	3.75	4.2	4.5	5.25	5.7	6.3

Step-2: Sum the water-depth for the whole profile.

Several approaches are used to determine total water from neutron moisture meter reading:

Approach-1: Total water-depth, $W_T = (1.5 \times W_1 + W_2 + W_3 + \ldots\ldots\ldots + 0.5\, W_n)$
Approach-2: Total water-depth, $W_T = (W_1 + W_2 + W_3 + \ldots\ldots\ldots + W_n)$

Using approach-1, total water depth = 29.7 cm

Conversion of weight basis soil moisture to volume basis moisture

Gravimetric moisture content is converted to volumetric moisture as follows:

$$\%\text{volume moisture content} = \%\text{weight basis moisture content} \times \text{bulk density of the.}$$

7.2.7 Workout Problems

Example 7.1. In a small irrigation farm, the following hydrological data are available for a particular time period:

Rainfall	250 mm
Surface runoff	50 mm
Ponded water depth at the end of time period	0 (zero)
Evapotranspiration	60 mm
Estimated deep drainage beyond one meter depth	20 mm
Upward flux from the groundwater/saturated layer to the top 1 m	0 (zero)

Determine the change of moisture storage within the top 1 m soil layer at the end of time period.

Solution. Change in moisture storage = inflow−outflow
i.e., ΔSM = (rainfall + initial ponded water + upward flow) − (surface runoff + final ponded depth + ET + Drainage)
= (250 + 0 + 0) − (50 + 0 + 60 + 20)
= 250 − 130 = 120 mm (Ans).
i.e., soil moisture storage increased by 120 mm depth of water.

Example 7.2. From an agricultural field, gravimetric soil samplings were done from different soil layers and weights were recorded before and after oven-dry. Layer-wise moisture data and bulk density are as follows:

Soil depth (cm)	Weight before oven-dry (gm)	Weight after oven-dry (gm)	Bulk density (gm/cm^3)
0–20	220	180	1.1
20–40	210	172	1.2
40–60	200	165	1.3
40–80	240	195	1.4

Determine the total moisture of the soil profile in terms of water depth.

Solution. We know,
Weight of moisture = initial (before oven-dry) weight − weight after oven-dry
Moisture percentage (wt. basis) = (wt. of moisture/oven-dry soil wt.) × 100
Moisture percentage in volume basis = moisture percentage in wt. basis × bulk density
X % moisture (vol. basis) means that X cm moisture exists in 100 cm soil depth. Thus for 20 cm depth it is: $(X/100)\times 20$
Calculation summary:

Soil depth	Moisture wt. (gm)	Wt. of dry soil, (gm)	% moisture, wt. basis	Bulk density (gm/cm^3)	% moisture, vol. basis	Moisture, in depth (cm)
0–20	40	180	22.2	1.1	24.4	4.9
20–40	38	172	22.1	1.2	26.5	5.3
40–60	35	165	21.2	1.3	27.6	5.5
60–80	45	195	23.1	1.4	32.3	6.5

Total moisture within the profile = 4.9 + 5.3 + 5.5 + 6.5 = 22.2 cm (Ans.)

Example 7.3. Soybean is cultivated in a field. The crop has a good vegetative growth and soil surface cover. About 90% of the incoming solar radiation is intercepted by the crop. If the evaporation from surrounding fellow soil is 6 mm/day, determine the evaporation from the soybean field.

Solution. We know,

$$E_c = E_f(1 - i)$$

Here, $E_f = 0.6$ mm/day

$$i = 0.90$$

Thus, $E_c = 6\ (1 - 0.9) = 0.6$ mm/day (Ans.)

Example 7.4. In a rice field, levees are provided to arrest the rainwater. Estimate the amount of surface runoff from a rainfall event of 150 mm, if the height of the levee around the field plot is 15 cm and the height of water in the field before rainfall is 5 cm.

Solution.

$$\begin{aligned}\text{Runoff amount} &= \text{rainfall} - (\text{height of levee} - \text{height of water in the field} \\ &\qquad \text{before rainfall}) \\ &= 15.0 - (15 - 5) \\ &= 15 - 10 \\ &= 5\text{cm(Ans.)}\end{aligned}$$

Example 7.5. A depth of 80 mm water was applied to a saturated paddy field through irrigation. After 3 days (72 h) of irrigation, the water depth was found 60 mm. During this period, there was 30 mm rainfall and 10 mm surface runoff. Average evapotranspiration for those days was 5 mm/day. Calculate seepage and percolation losses in the field.

Solution.

$$\begin{aligned}\text{Change in storage} &= \text{inflow} - \text{outflow} \\ &= (\text{irrigation} + \text{rainfall}) \\ &\quad - (\text{runoff} + \text{ET} + \text{seepage and percolation})\end{aligned}$$

i.e., $60 = (80 + 30) - (10 + 5\times3 + \text{SP})$
or SP = 25 mm (Ans.)

Example 7.6. A slope gauge having a scale with a slope of 1 vertical to 4 horizontal was installed in a paddy field to measure the water loss in a field. The scale reading at 6:00 AM was 85 mm and that after 48 h was 25 mm. The evapotranspiration and rainfall during this period were 8 mm and 2 mm, respectively. Calculate the seepage and percolation loss of water in the field.

Solution. Difference in scale reading = 85 − 25 = 60 mm
Scale is 1 vertical 4 horizontal
Thus, vertical drop of water level = 60/4 = 15 mm
From water balance equation,

Inflow = outflow ± change in storage

i.e., Rainfall = evapotranspiration + seepage and percolation ± change in water depth

$2 = 8 + SP - 15$ [−ve sign for drop, decrease in storage]

thus, $SP = 9$ mm (Ans.)

Example 7.7. A groundwater formation underlying a hydrological basin has a porosity of 60% and specific retention of 20%. During a calendar year, the fluctuation of water level in an observation well was found 2.0 m. Determine the amount of deep percolation during the year.

Solution.

$$\begin{aligned}\text{Specific yield}, S_y &= \text{porosity} - \text{specific retention}\\ &= 60\% - 20\% = 40\%\end{aligned}$$

$= 60\% - 20\% = 40\%$
Deep percolation, $D = h \times S_y$
Here, fluctuation of water-table, $h = 2$ m
Thus, $D = 2 \text{ m} \times (40/100)$
= 0.80 m (Ans.)

Example 7.8. The hydraulic potential of two points at a soil layer below 1.0 m depth and the moisture dependent hydraulic conductivity are given below:

	Time (h): 10:00		11:00		12:00		13:00	
	Point-1	Point-2	Point-1	Point-2	Point-1	Point-2	Point-1	Point-2
Hydraulic potential, (cm)	92	105	108	120	90	100	85	101
K (cm/h)	0.5		0.8		0.7		0.6	

The difference in distance between the points is 15 cm. Determine the upward flux from point-2 to point-1 during the given time period.

Solution. We know, flux, $q = K(\mathrm{d}H/\mathrm{d}z)$.

The steps are summarized in Table, given below:

	Time (h): 10:00		11:00		12:00		13:00	
	Point-1	Point-2	Point-1	Point-2	Point-1	Point-2	Point-1	Point-2
Hydraulic potential (cm)	92	105	108	120	90	100	85	101
Potential difference between points, H (cm)	13		12		10		16	
z (cm)	15		15		15		15	
$\mathrm{d}H/\mathrm{d}z$	0.87		0.80		0.7		0.6	
K (cm/h)	0.5		0.8		0.7		0.6	
q (cm^3/cm^2/h)	0.43		0.60		0.47		0.64	

$$\begin{aligned}\text{Total flux for the period (3h)} &= 0.43 + 0.64 + 0.47 + 0.64 \\ &= 2.18\ \mathrm{cm}^3/\mathrm{cm}^2 (\text{Ans.})\end{aligned}$$

Average flux = 2.18/3 = 0.73 cm^3/cm^2/h (Ans.)

Example 7.9. For a hydrologic basin, the following empirical equation has been established for groundwater contribution (G_c) to the crop evapotranspiration (ET):

$$\frac{G_\mathrm{c}}{ET} = 0.8 - 0.55D,$$

where D is the depth to groundwater (m)

For a hybrid corn of 160 days duration, the depth to groundwater for 1–40, 40–80, 80–120, and 120–160 days period are 1.2, 1.3, 1.1 and 1.0 m, respectively. Determine the groundwater contribution in terms of:

(a) ET
(b) Absolute water depth, if the ET for the 1–40, 40–80, 80–120, and 120–160 days period are 60, 75, 80, and 60 mm, respectively.

Solution. Using the equation $G_\mathrm{c}/ET = 0.8 - 0.55D$,

the ratio G_c/ET for a depth 1.2 m = 0.14 m.
Thus, $G_\mathrm{c} = 0.14$ ET
For ET = 60 mm, $G_\mathrm{c} = 0.14 \times 60 = 8.4$ mm

The results for other periods are summarized below.

Days	1–40	40–80	80–120	120–160
D (m)	1.2	1.3	1.1	1.0
G_c/ET	0.14	0.085	0.195	0.25
ET (mm)	60	75	80	60
G_c (mm)	8.4	6.4	15.6	15

Thus,

(a) Groundwater contribution for the period in terms of ET are 0.14 ET, 0.085ET, 0.195ET, and 0.25ET, respectively (Ans.).

(b) Absolute G_c for the periods are 8.4 mm, 6.4 mm, 15.6 mm, and 15 mm, respectively, and total groundwater contribution is 45.4 mm. (Ans.)

Relevant Journals

- Agricultural Water Management
- Transactions of the ASAE
- Journal of Hydrology
- Hydrological Process
- Irrigation Science
- Vadose zone Journal
- Journal of Hydrology and Hydromechanics
- Water Resources Research
- Irrigation and Drainage system

FAO Papers

- Irrigation and Drainage Paper No. 39 (Lysimeters)
- Irrigation and Drainage Paper No. 56 (Crop evapotranspiration)
- Soils Bulletins 68 (Field measurement of soil erosion and runoff)

Questions/Exercises

1. What do you mean by field water balance? Give its mathematical form and schematic view.
2. Discuss the limiting conditions of the components of field water balance.
3. What is evapotranspiration (ET)? Discuss in brief the factors affecting ET.
4. Discuss the direct and indirect methods for estimating ET.
5. What is crop coefficient (K_c)? What do you mean by single and duel crop coefficient? What are the factors affecting crop coefficient?
6. Narrate the various ways for expressing K_c.
7. Narrate the process of evaporation. What is its importance in water management?
8. What are the factors affecting evaporation from crop field and free water body?
9. How you can estimate evaporation from meteorological data?
10. Give a neat sketch of USWB Class A pan. Discuss the procedure for setting and measurement with USWB Class A pan.
11. Write down the equation expressing the effect of salinity on evaporation.
12. How you will estimate surface runoff from the field?

13. What is deep percolation? What are the factors affecting deep percolation?
14. Discuss the various methods for measuring deep percolation. Give typical values of deep percolation for major soil groups.
15. What is upward flux? What are the factors affecting upward flux?
16. Briefly narrate the methods for calculating upward flux under both the (a) presence, and (b) absence of zero flux plane.
17. Write down different equations for estimating upward flux/water-table contribution in crop field.
18. Narrate the procedure for calculating the change in soil-moisture storage over time.

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Chapter 8
Soil–Water–Plant–Atmosphere Relationship

Development of sustainable irrigation practices will require that we understand better the biophysical processes of root-water uptake in soil, and transpiration from plant canopies. Solar energy is the driving force for most of the biophysical processes in the plant system and water movement from soil to the atmosphere. Details regarding soil, water, plant, and atmosphere (weather and climate) are described in the respective chapters. In this chapter, mostly the interactions among them are described.

8.1 Concept of Soil–Plant–Atmospheric Continuum

Movement of water occurs in response to differences in the potential energy of water (from an area of relatively high-water potential to an area of relatively low-water potential). Although water uptake by plants is under physiological control, it is often described as a purely physical process, as a consequence of gradients in water potential in the soil–plant–atmosphere continuum (SPAC). The SPAC is the pathway for water moving from soil through plants to the atmosphere. The SPAC constitutes a physically integrated, dynamic system in which various flow processes (e.g., solar energy interception, plant transpiration, water movement through plant system, and water movement from soil to plant root hair) occur simultaneously and independently, like links in a chain.

A plant grows in soil and opens to atmosphere. About 99% of all the water that enters the roots leaves the plant's leaves via the stomata without taking part in metabolism. On a dry, warm, sunny day, a leaf can evaporate 100% of its water weight in just an hour. Water loss from the leaves must be compensated for by the uptake of water from the soil. Water movement is due to differences in potential between soil, root, stem, leaf, and atmosphere. Under normal conditions, the water potential in soil is higher than that in root saps or fluids. Typical moist soil might have a water potential of about -0.3 to -1.0 bar, root tissue about -4.0 bar, stem about -7.0 bar, leaf about -10.0 to -12.0 bar, and typical dry atmosphere about

M.H. Ali, *Fundamentals of Irrigation and On-farm Water Management: Volume 1*,
DOI 10.1007/978-1-4419-6335-2_8,

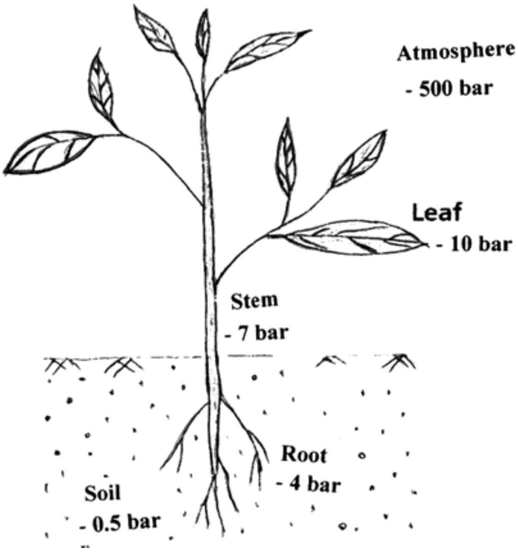

Fig. 8.1 Water movement in soil–plant–atmospheric continuum

−400 to −600 bar. These differences in water potential (and hence potential gradient) are the driving force for causing the water movement (Fig. 8.1).

Water potential of the atmosphere is computed as:

$$P_{\text{atm}} = [(R \times T)/M_{\text{W}}] \times \ln(e/e^{*}),$$

where R = gas constant = 8.31 J/mol/K, T = Temperature (K) = C + 273, M_{W} = molecular weight of water = 18 g/mol, and e/e^{*} is the relative humidity.

8.1.1 Some-Related Concepts/Terminologies

8.1.1.1 Water Potential

It is the difference in water energy between two regions containing water. Potential is defined as the thermodynamic measure of energy with water, and the available energy to do work. Water potential is usually measured in units of the pressure needed to stop water movement. Commonly used units are Mega Pascals (MPa), bar, etc. By convention, pure water is said to have a potential of zero. If any solute (substance that dissolves) is dissolved in pure water, the water potential of that solution decreases [and hence negative (lower than zero) water potential], attracting free water across a semipermeable membrane. Water under pressure will have positive potential and move to areas of lower pressure. Water that is elevated will have positive potential and move to lower areas.

8.2 Soil–Water–Plant–Atmosphere Interrelations

8.2.1 Different Soil–Water Coefficients

Irrigation water management at any level requires a thorough understanding of the relations between soil and water. These relations are governed by intermolecular forces and tensions, which give rise to the "capillary phenomenon." These forces in unsaturated soils are influenced by soil texture and structure. It is on the basis of the soil texture and structure that water retention capacity or water holding capacity of the soil varies.

8.2.1.1 Field Capacity

The soil is at field capacity when all the gravitational water has been drained and a vertical movement of water due to gravity is negligible. Further water removal for most of the soils will require at least 7 kPa (7 cbars) tension.

8.2.1.2 Permanent Wilting Point

The permanent wilting point is the point/situation where there is no more water available to the plant. The permanent wilting point depends on plant variety, but is usually around 1,500 kPa (15 bars). This means that for the plant to remove water from the soil, it must exert a tension of more than 1,500 kPa (15 bars). This is the limit for most plants, and beyond this they experience permanent wilting.

8.2.1.3 Saturation Capacity

It is the moisture content of soil when all the pores are filled with water. In clayey soil, the porosity is highly variable as the soil alternatively swells and shrinks, aggregates and disperses, compacts and cracks. Since clayey soils swell upon wetting, the relative volume of water at saturation can exceed the porosity of the dry soil.

8.2.1.4 Water Holding Capacity or Water Retention Capacity

Water is held within the soil matrix by adsorption at the surfaces of particles and by capillarity in the pores. The size, shape, and arrangement of the soil particles and the associated voids (pores) determine the ability of the soil to retain water. It is important to realize that large pores in the soil can conduct more water more rapidly than fine pores. In addition, removing water from large pores is easier and requires less energy than removing water from smaller pores.

Sandy soils consist mainly of large mineral particles with very small percentages of clay, silt, and organic matter. In sandy soils, there are many more large pores than in clayey soils. In addition, the total volume of pores in sandy soils is significantly smaller than in clayey soils (30–40% for sandy soils compared with 40–60% for clayey soils). As a result, much less water can be stored in sandy soil than in the clayey soil. It is also important to realize that a significant number of the pores in sandy soils are large enough to drain within a few hours (largely the first 24 h) because of gravity and this portion of water is lost from the system before the plants can use it.

8.2.1.5 Effect of Load on Water Retention

Effect of load on soil specimen is that it reduces the void or pore space, and thus it affects the water retention capacity.

8.2.1.6 Maximum Available Moisture or Maximum Plant Available Moisture

Maximum available soil moisture (MASM) is the moisture content between field capacity (FC) and wilting point (WP), i.e.,

$$\mathrm{MASM} = \mathrm{FC} - \mathrm{WP}.$$

In terms of water depth, it is expressed as:

$$d_{\mathrm{masm}} = \frac{\mathrm{FC} - \mathrm{WP}}{100} \times D,$$

where d_{masm} is the maximum available soil water in cm depth, FC is the moisture at field capacity (%), WP is the moisture at wilting point (%), and D is the root depth (cm).

For soils having different layers, the total maximum available soil moisture (TMASM) within the root zone can be expressed as:

$$d_{\mathrm{masm}} = \sum_{i=1}^{n} \frac{(\mathrm{FC}_i - \mathrm{WP}_i)}{100} \times D_i, \tag{8.1}$$

where $\mathrm{FC_i}$ is the soil moisture at field capacity for *i*th layer (% vol), $\mathrm{WP_i}$ is the soil moisture at wilting point in *i*th layer (% vol), D_i is the depth of *i*th layer (cm), and n is the number of subdivisions/layers of the effective rooting depth.

Maximum available moisture for various soil types is given in Table 8.1.

Table 8.1 Maximum available moisture for various soil types

Type of soil	Available water	
	Range (cm/m)	Average (cm/m)
Sandy soil	5–10	7.5
loam	10–12	11
Silt	12–15	13.5
Clay	15–20	17.5

8.2.1.7 Maximum Readily Available Moisture

It is the portion of the maximum available moisture that is easily extractable by the plant. It may be 60–75% of the maximum available moisture depending on soil, plant type (crop cultivar), species, and stage of crop.

8.2.1.8 Presently Available Soil Moisture

Presently available soil moisture (PASM) is the moisture currently (i.e., at present state of the crop and soil) available for plant abstraction. It is equal to the difference between the present soil-water content (θ) and moisture content at permanent wilting point (θ_{PWP}) and i.e.,

$$\mathrm{PASM} = \theta - \theta_{\mathrm{PWP}},$$

where all the terms are expressed in percent volume.

To express the moisture in terms of water-depth (for a particular soil layer), it is calculated as:

$$\mathrm{PASM} = \frac{\theta - \theta_{\mathrm{PWP}}}{100} \times D,$$

where PASM is the presently available soil moisture (cm), FC is the soil moisture at field capacity (by volume percent), θ is the soil moisture content (by volume percent), and D is the depth of the soil layer under consideration (cm).

Total presently available soil moisture (TPASM) is the sum of the available moisture within the root zone.

$$\mathrm{TPASM(cm)} = \sum_{i=1}^{n} \frac{\theta_i - \theta_{\mathrm{PWP}_i}}{100} \times D_i, \tag{8.2}$$

where $\theta_{\mathrm{PWP}i}$ is the soil moisture at permanent wilting point for ith layer (% vol), θ_i is the present soil moisture content in ith layer (% vol), D_i is the depth of ith layer (cm), and n is the number of subdivisions of the effective rooting depth.

8.2.1.9 Depletion of Available Soil Water

The percentage depletion of available soil-water is the lowering of current state of soil-moisture from field capacity with respect to theoretical maximum possible available soil-moisture.

The percentage depletion of available soil-water in the effective root zone can be estimated using the following equation:

$$\text{Depletion}(\%) = \frac{1}{n}\sum_{i=1}^{n}\frac{\text{FC}_i - \theta_i}{\text{FC}_i - \text{PWP}_i}, \tag{8.3}$$

where FC_i is the soil moisture at field capacity for ith layer (v/v), θ_i is the soil moisture in ith layer (v/v), PWP_i is soil moisture at permanent wilting point for ith layer (v/v), and n is the number of subdivisions of the effective rooting depth to be used in the soil moisture sampling.

8.2.1.10 Air Entry Suction or Air Entry Potential

In a saturated soil at equilibrium with free water at the same elevation, the equilibrium pressure is atmospheric. In that case, the hydrostatic pressure and the suction are zero. If a slight suction is applied to water in a saturated soil, no outflow may occur until suction is exceeded certain critical value at which the largest pores begin to empty. This critical suction is called the air-entry suction.

Water moves due to “potential difference” between two points in a system *or* due to “capillary force.” In soil system, “potential” or “energy difference” acts under both saturated and unsaturated condition. But the “capillary force” acts only under unsaturated condition.

8.2.2 Plant–Water Relations

Plant–water relations concern how plants control the hydration of their cells, including the collection of water from the soil, its transport within the plant, and its loss by evaporation from the leaves (transpiration). Transpiration accounts about 60–70% of evapotranspiration, and is related to leaf stomatal conductance and water potential. Plant water status is a function of soil water availability, hydraulic resistance along the water flow path, plant water capacitance, and meteorological conditions that determine atmospheric evaporative demand (i.e., atmospheric water potential). Rapid change in climatic conditions may cause abrupt changes in plant water status.

A well-hydrated leaf may transpire several times its own volume of water during a day. Water evaporates from wet cell walls into the internal gas spaces of the leaf.

It then flows away as vapor, largely through stomata, which are variable pores in the lower surface of the leaf. The loss is an unavoidable consequence of the stomata being open, as they must allow carbon dioxide to enter the leaf. Only a very small fraction (<1%) of the water absorbed by plants is used in photosynthesis, while most (>99%) is lost as vapor.

Well-watered plants maintain their shape due to the internal pressure in plant cells (turgor pressure). This pressure is also necessary for plant cell expansion and consequently for plant growth. The pressure may be high as 1 MPa, about 10 times the pressure of atmosphere. Plants perform best when they are turgid. Loss of this pressure due to insufficient water supply can be noticed as plant wilting. Turgidity of a cell is defined as the ratio between the water content of the cell and the water content at full turgidity, where full turgidity is obtained at equilibrium with water at its state. Actually, turgidity of a cell is the relative turgidity, which indicates the deviation of the actual situation from the possible maximum. Turgor pressure is important for the mechanical support of most leaves. Function of the guard cells surrounding the stomatal openings is almost certainly regulated by the turgor pressure.

8.2.3 Soil Wetness and Evaporation Relationship

The evaporation of water directly from the soil is often an important component of water loss from the crop field. The factors that influence evaporation from the soil are air temperature, wind speed, atmospheric humidity, radiation, and water available in the soil (soil wetness). It is strongly dependent on soil wetness and on plant cover. When the leaf area index reaches 4 or more, even with wet soil, soil evaporation is only about 5% of the total. However, when the leaf area index is 2 or less, wet soil evaporation can be as much as half the total. When the soil surface resistance is close to zero (i.e., after rain or irrigation), about 10 mm of soil evaporation can occur at a high rate. As the soil dries, the surface resistance increases and soil evaporation decreases significantly. With a dry soil surface, soil evaporation is relatively unimportant, and water loss is solely by transpiration from plant leaves and this is approximately proportional to leaf area index, if the other factors remain constant.

In the absence of gravity effect, the amount of water removed through evaporation from the soil with uniform water content and constant suction at the surface is proportional to the square root of time, and the proportional constant is termed desorptivity (like sorptivity, desorptivity is a soil hydraulic property).

Evaporation of water from initially saturated soil into a constant environment occurs in three stages. The first stage is referred to as the constant rate stage. At this stage, water is not limiting and evaporation is controlled by meteorological conditions. In the tropics, where the loss of soil water through evaporation is of paramount importance, the appropriate time to control soil evaporation would be the constant rate stage. The application of surface mulch would reduce the influence of atmospheric evaporativity and limit soil water loss during the constant rate stage. The second stage is the falling rate stage. At this stage, evaporation rate falls rapidly because water loss is limited by the rate of water transport through the drying soil. Evaporation at this stage is governed by the soil hydraulic properties, and is relatively insensitive to atmospheric evaporativity. The third stage occurs when the soil surface layer is sufficiently dry. Evaporation then becomes sensitive to the heat flux in the soil, and transmission of water owing to external source of radiation occurs primarily by vapor diffusion, which is a slow process. At this stage, evaporation is proportional to the square root of time. Therefore, if the aim is to fallow the soil to store water for future crop use, then loosening the soil surface by shallow tillage would cause the soil surface to dry quickly to form a dry soil mulch, which would break soil pore continuity so that desorptivity would be minimized.

8.2.3.1 Empirical Equation of Evaporation from Soil

The rate of evaporation e is given by (Gardner 1959):

$$e = (\theta_{\mathrm{i}} - \theta_0)(\overline{D}/\pi t)^{1/2}, \tag{8.4}$$

where $\overline{D}$ is the weighted mean diffusivity, θ_{i} is the initial soil water content, θ_0 is the final water content, and t is time.

Integrating with respect to t, evaporation (E) is obtained as:

$$E = 2(\theta_{\mathrm{i}} - \theta_0)(\overline{D}t/\pi)^{1/2}. \tag{8.5}$$

It is assumed that $\overline{D}$ is a constant, and thus we can write E as:

$$E = S_{\mathrm{d}} t^{1/2}, \tag{8.6}$$

where $S_{\mathrm{d}} = 2(\theta_{\mathrm{i}} - \theta_0)(\overline{D}/\pi)^{1/2}$.

Analogous to sorptivity (Philip 1957), the constant S_{d} is termed as desorptivity. Desorptivity is a soil hydraulic property used to describe the ability of soil to lose water by evaporation.

8.2.4 Root Water Uptake in Relation to Soil-Moisture

Models of water uptake by plant roots generally have one of two purposes. Either they produce estimates of transpirational water loss for water budget models or they provide estimates for predicting plant water stress. Water uptake and transport through the root system can be described using a saturated Darcy-equation.

Soil-water suction increases as soil wetness decreases. As a result, the plant water suction required to extract water from the soil must increase correspondingly.

The soil will deliver water to the root as long as the water suction in the root is greater than the soil.

A differential equation for the uptake of water by a single root is given by:

$$\frac{q}{A} = -k\frac{\mathrm{d}\Psi}{\mathrm{d}r}, \tag{8.7}$$

where q is the flux of water (kg s^{-1}), A is the area of flow (m^2), k is the soil hydraulic conductivity (kg s^{-1} m^{-2}), ψ is the matrix potential (kPa), and r is the radial distance from the root axis (m).

The area for water flow, $A = 2\pi rl$, where l is the length of the root. Hydraulic conductivity can then be related to water potential using the term

$$k = k_\mathrm{s}\left(\frac{\Psi_\mathrm{e}}{\Psi}\right)^n, \tag{8.8}$$

where k_s is saturated conductivity (kg s^{-1} m^{-2}), ψ_e is the air entry potential (J kg^{-1}), and n is a constant that depends on soil texture and ranges typically from 2 to 3.5.

8.2.4.1 Flow of Water to Plant Roots

A typical root can be represented by an infinitely long, narrow cylinder of constant radius and absorbing characteristic, and the soil-water movement toward the root is radial; the approximate form of the flow equation is:

$$\frac{\partial\theta}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD\frac{\partial\theta}{\partial r}\right), \tag{8.9}$$

where θ is the volumetric soil wetness, t is the time, r is the radial distance from the axis of the root, and D is the diffusivity.

Assuming constant flux at the root surface, Gardner solved this equation subject to the following initial and boundary conditions: $\theta = \theta_0$, $\psi = \psi_0$, $t = t_0$

$$q = 2\pi aK\frac{\partial\varphi}{\partial r} = 2\pi aD\frac{\partial\varphi}{\partial r}, \quad r = a, t > 0, \tag{8.10}$$

where a is the root radius, φ is the matric suction; K, the conductivity; and q, the rate of water uptake per unit length of root. With K and D assumed to be constant, the following solution is obtained:

$$\varphi - \varphi_0 = \Delta\varphi = \frac{q}{4\pi K}\left(\ln\frac{4Dt}{r^2} - \gamma_\mathrm{c}\right), \tag{8.11}$$

where γ_c is Euler's constant.

From this equation, it is possible to calculate the gradient that will develop at any time between the soil at a distance from the root and the suction at the root-to-soil contact zone. The above equation explains that the gradient is directly proportional to the rate of water uptake and inversely proportional to the hydraulic conductivity. Therefore, the root-water suction is expected to depend on these two factors as well as on the average soil-water suction. Since the diffusivity D appears in the logarithmic term, it seems that variations in D would cause only slight changes in the gradient. Therefore, the assumption of a constant D does not introduce a major error.

The above equation also explained that, the suction difference between soil and root ($\Delta\phi$) needed to maintain a steady flow rate, which depends on the conductivity K and the flow rate q. When the soil suction is low and conductivity is high, $\Delta\phi$ is small (i.e., the suction in the root does not differ markedly from the suction in the soil). When the soil water suction increases, and consequently the soil water conductivity decreases, the suction difference (hence the gradient) needed to maintain the same flow rate must increase correspondingly.

Recent experimental evidence shows that (Teuling et al. 2006) plants can compensate for water stress in the upper, more densely rooted, soil layer by increasing the water uptake from deeper layers. By adapting root water uptake to water availability, plants are able to extend the period of unstressed transpiration.

8.2.5 Hydraulic Conductance in Soil–Leaf Pathway

Hydraulic conductance in soil–leaf pathway can be estimated from the model of Mishio and Yokoi (1991). The rate of change of leaf water content is given as:

$$\frac{\mathrm{d}W}{\mathrm{d}t} = g(\Psi_\mathrm{s} - \Psi_\mathrm{l}) - E, \tag{8.12}$$

where W is the leaf water content, g is the hydraulic conductance in the soil–leaf pathway, ψ_s is the soil water potential, ψ_l is the leaf water potential, and E is the transpiration rate.

The integrated form of the above equation is:

$$\mathrm{W}_{\mathrm{t}2} - \mathrm{W}_{\mathrm{t}1} = \int g(\Psi_\mathrm{s} - \Psi_\mathrm{l})\mathrm{d}t - \int E\mathrm{d}t. \tag{8.13}$$

When the interval from time 1(t1) to time 2 (t2) is relatively short (e.g., few hours), the conductance, g, will be essentially constant as it depends primarily on plant structure, such as the number and diameter of vessels in the root and stem. Equation (8.13) is thus rewritten as:

$$W_{\mathrm{t}2} - W_{\mathrm{t}1} = g \int (\Psi_\mathrm{s} - \Psi_\mathrm{l})\mathrm{d}t - \int E\mathrm{d}t,$$

or,

$$W_{t2} - W_{t1} + \int E\mathrm{d}t = g \int (\Psi_s - \Psi_l)\mathrm{d}t \tag{8.14}$$

From the above equation, the hydraulic conductance, g, can be obtained. The left-hand size of the equation corresponds to the calculated water supply from soil to leaf, and $\int(\psi_s - \psi_l)\mathrm{d}t$, the cumulative water potential difference in the soil–leaf pathway.

8.2.6 Plants Response to Soil Moisture Deficit

Before going through details regarding the effects of water stress or soil moisture deficit on plant growth and yield, it is worth defining the *stress*. Stress may be defined as the situation in context to existing rooting condition, where the roots cannot supply water to meet the plant's evapotranspiration (ET). In the literature, stress or soil moisture deficit is commonly defined as the drop of moisture in the root zone below field capacity. One important thing should be taken into account here that the moisture in the active root zone (the zone within which about 80% of the roots are concentrated) should be enough to supply the ET demand. During the early stage of the crop, roots are concentrated over 15–20 cm of the top soil. This layer may be dry and the layer beneath this may be sufficiently wet, which can provide no benefit. Moisture outside the active root zone, where root density is low or roots are not mature enough, can not benefit so much.

Almost 60–75% of the moisture between field capacity and wilting point (referred to as available moisture) is readily available to plants except the sensitive crops. Drop of 50–60% of the available moisture is not stress at all for most crops grown under normal conditions. Another aspect is that irrigation at a particular growth stage does not end its effect (i.e., moisture supply) at this stage only, but also provides moisture to the next stage.

8.2.6.1 Factors Affecting Plant Response to Water Stress

The response of plants to water deficits and the interaction with the variable environment is complex because conditions vary with the following:

- The frequency of deficit or drought and wet periods
- The degree and duration of deficit
- The speed of onset of deficit
- The patterns of soil water deficits and/or atmospheric water deficits
- The sequence of deficit
- The history of deficit

- The cultivar or species
- The duration of the crop
- The growth stages of the crop at which stress was imposed

The Frequency of “Deficit or Drought” and Wet Periods

Effect of soil moisture deficit on plants depends on the frequency of deficit and wet periods. Higher frequency of wet periods and lower frequency of drought throughout the growing season affects plant processes to a lesser extent, and vice versa.

Degree and Duration of Drought

The extent of adverse effects of drought depends on the degree and duration of drought. If the degree of drought is high, reaching close to permanent wilting point, then the effects can be irreversible. That is, the plants would not regain their original state, although sufficient water is applied later on. Drought of small duration through the plant growing season in comparison to drought of long duration at a stretch, can affect the plant to a lesser extent.

The Speed of Onset of Drought

If the soil moisture storage within the root zone is high, the speed of onset of drought would be low, and thus there would be more opportunity for osmotic adjustment and as a result, less deleterious effect on plant growth and development. For this reason, the effect of water deficit in pot culture is more detrimental than field crop. On the other hand, for high atmospheric water demand, the speed of onset of deficit will be high, while it will be low for low atmospheric demand.

The Pattern of Soil-Water Deficit

The rate of water uptake from each soil layer depends on the root density of that layer. As a result, the layer having higher root density can effectively abstract soil moisture. Soil water deficit at higher rooting zone and available moisture at lower rooting zone can affect more than that of having available soil moisture at higher rooting zone and low moisture at lower rooting zone.

The Sequence of Deficit

The effect of deficit heavily depends on the sequence of deficit because adaptive response and/or sensitivity depend on it. If the deficit is allowed or imposed in alternate sequence (i.e., irrigation – deficit – irrigation – deficit), hardening processes take place and make the plants less sensitive to renewed water stress.

The History of Deficit

The impact of water stress depends on the stress history (i.e., whether any stress occurs prior to this stress). If the plants are subjected to some degree of water stress prior to this stress (i.e., earlier time), the plants will be less sensitive to renewed water stress.

The Cultivar or Species

All plants are not genetically similar, and hence their ability to tolerate drought or water stress is not same. Some plants have a drought tolerance mechanism, some have a drought avoidance technique, while some are sensitive to drought.

Growth Stage of the Crop

Responses of various growth processes to water stress largely depend on the timing of drought in relation to crop growth stages. All growth stages are not similar in their response to drought. For most field crops, the early stage (when the root system is not fully developed or matured, or not deeply rooted) and the booting –heading stage are sensitive to soil moisture deficit. Stress imposed at the early growth stage extracts less soil-water than that at the mature stage.

8.2.6.2 Effects of Water Stress on Plant System

Dry matter production by crops is a function of the rate of establishment, size and duration of the canopy, and the CO_2 fixation efficiency of that canopy. All these factors can be affected by plant water deficits to a greater or lesser degree. The major economic consequence of insufficient water in agricultural crops is yield reduction. When too little water is available in the root zone, the plant will reduce the amount of water lost through transpiration by partial or total stomatal closure. This results in decreased photosynthesis, since the CO_2 required for this process enters the plant through the stomata. Decreased photosynthesis reduces biomass production and results in decreased yields.

The process most sensitive to water stress is cell growth. The primary effect appears to be a physical one. When the turgor pressure in a plant cell falls due to water stress, cell expansion is decreased due to lack of pressure within the cell. There is a close correlation between decrease in cell size and the degree of water stress in plant tissues. The outside pressure of a plant leaf remains atmospheric and is transmitted to the interior via the cell wall system. The leaf structure is better suited to withstanding an excess internal vacuolar pressure through elastic extension than to balancing this excess external pressure through compression of cell walls. Because of severe stress, cell water content is reduced, resulting in a reduced turgidity. Under this situation, due to external atmospheric pressure, the walls in mesophytic tissues tend to collapse and the cells shrivel/shrink. This process is called cytorrhysis, which is a major mechanism of injury under severe drought.

Severe water stress directly affects enzyme levels in plants. Under moderate stress some enzyme levels are raised, for example, the enzyme involved in hydrolysis and dehydrogenation. In general, however, water stress results in decrease in enzyme level.

The relationship between water stress and plant hormones is complex. In minor to moderate water stress, there is a rapid accumulation of abscisic acid (ABA). Plant senescence is accelerated by ABA, thus the plants become senescent more rapidly under water stress. This results in rapid translocation of carbohydrates and/or sugar (assimilates) from stems and leaves to grain if some stress is imposed at early grain filling stage.

The common responses of crop plants to soil moisture deficit are on the following sector of crop growth, development, grain or seed yield, quality, and resource use efficiency:

- Germination
- Plant stand
- Tillering
- Leaf area index
- Turgidity and/or plant–water relations
- Effective tiller
- Anthesis initiation
- Pollination
- Duration of ripening
- Nutrient uptake
- Soil moisture extraction
- Unit seed weight
- Dry matter yield
- Assimilate partitioning or harvest ratio
- Nutrient content of seeds
- Radiation use efficiency
- Water use efficiency

Germination

For proper germination of crop seed, a certain percentage of soil moisture is needed. Below this level, the germination is hampered. In some cases, germination fails or is delayed, or the germination percentage is reduced. The minimum required soil moisture level for common crops is given below:

Crop	Minimum soil moisture (% vol) required for proper germination[a]
Rice	26
Wheat	24
Pulses	22
Oil seeds	22

[a] For loamy soil., The figures may vary with soil type,and also depends on drying rate

Under dry conditions, it is important to ensure that the seeding operation leaves the seed covered with well-packed soil. Loose soil fill is subject to greater drying, and seeds that are not covered will often fail to germinate even moisture conditions are favorable.

Plant Stand

After completion of germination, the moisture is extracted through the root apex (crown root in cereals). In the absence of sufficient moisture, the roots cannot extract moisture and plant mortality is increased. Thus, the stand of plant is reduced and/or it becomes an unhealthy plant. The unhealthy plants cannot produce optimum tillers.

Tillering

Soil moisture deficit at tillering stage (or prior to this stage) reduces tiller per plant. If soil moisture is provided (through irrigation or rainfall) later to this stage, some tillers are initiated (referred to as late tillers) for crops such as wheat, which grow fast and mature almost at the same time of normal tillers.

Lai

Water stress during the early and vegetative growth stage produce the shorter plants with the least leaf area index.

Nutrient Uptake

Nutrient uptake is retarded due to water deficit. This happens because the applied fertilizer cannot dissolve and be released in plant available form to move to the nearest root hair. Although mineral absorption by roots is an active process using metabolic energy, roots can only absorb ions, which impinge on the surface of the roots. Thus, the flow of water through soil results in a flow of nutrient ions along the same pathway, so bringing nutrients into contact with the roots. If water deficits develop, rates of transpiration and water uptake fall. As the soil dries out to permanent wilting point, the movement of ions toward the rots will also be reduced. Some of the elements (such as nitrogen from urea fertilizer) can escape into atmosphere due to volatilization.

Yield Reduction

The major economic consequence of insufficient water in agricultural crops is yield reduction. When too little water is available in the root zone, the plant will reduce the amount of water lost through transpiration by partial or total closer of stomata. This results in decreased photosynthesis since the CO_2 required for this process enters the plant through the stomata. Decreased photosynthesis reduces biomass production and results in decreased yields. Ali (2008) reported that the lower yield in water-stressed wheat plants were associated with lower LAI, root length density, nutrient uptake, and yield components.

Assimilate Partitioning/Harvest Ratio

Because of water stress, higher remobilization of assimilate from vegetative parts to grain occurs. Thus, the harvest ratio increases (Ali et al. 2007).

Radiation Use Efficiency and Dry Matter Production

Radiation-use efficiency (i.e., dry matter production per unit intercepted radiation) of the young plants under drought condition is similar to that of the irrigated one, but total dry matter production reduces because of reduction in radiation interception (because of lower LAI).

8.2.7 Water Flow Through Soil–Plant–Atmospheric Continuum

Under natural conditions, the roots of a plant grow in moist soil whereas the stems and leaves grow in a relatively dry atmosphere. Water moves from the soil, through the plant, to the evaporating surfaces in the sub-stomatal cavities of leaves in response to gradients in decreasing water potential. Water flow through soil–plant–atmosphere is analogous to Ohm's law of current flow. The flow rate is directly proportional to potential difference in a soil-leaf pathway and inversely proportional to the resistance in the flow pathway. Steady-state water flow through a SPAC is expressed as:

$$E = \frac{\Psi_s - \Psi_l}{R} = g(\Psi_s - \Psi_l) \tag{8.15}$$

where E is the transpirational flux (mm/s), Ψ_s is the soil water potential (bar), Ψ_l is the leaf water potential (bar), R is the water flow resistance in a soil–leaf pathway (bar s mm^{-3}), and g is the hydraulic conductance.

The major resistances in the soil–leaf pathway include resistances due to the soil (R_s), soil interface (R_I), root endodermis (R_r), stem xylem (R_x), and leaf (R_L). Xylem resistance to water movement is assumed to be low, although it varies according to width. This form of flow rate is analogous to the well-known Darcy's law, where the reciprocal of resistance is replaced by conductance.

Conceptually, leaf water potential should be considered a function of flux rate and resistance (8.15) as:

$$\Psi_{\text{leaf}} = \Psi_{\text{soil}} - \text{flux} \times r_{\text{soil to leaf}}.$$

According to this equation, as soil water potential decreases or the flux rate or soil-to-leaf resistances increases, leaf water potential should become more negative.

The theories of water transpiration through soil–plant–atmospheric system have been described in Chap. 5 (*Plant*). Transpiration provides the major driving force for plant water absorption against the gravitational pull and frictional resistance in the water pathway through the plant. After addition of water to the soil and allowing the soil to drain gravitational water, the water potential of soil (ψ_{soil}) is about –0.3 bar. At night, the stomata are closed, water moves into the plant and the ψ_{soil} and ψ_{leaf} reaches equilibrium. During the day, the stomata are open and transpiration occurs, and hence water is lost from the leaf. Consequently, the ψ_{leaf} reduced, and creating a water potential (ψ_w) gradient. This provides the energy differential to cause water lost by transpiration. As long as the transpiration rate required for the plant is not too high, the hydraulic conductivity of the soil is adequate and the density of the roots is sufficient, the plant can extract water from the soil at the rate needed to maintain normal activity. When the rate of extraction drops below the rate of transpiration (due to high evaporative demand or low soil-water conductivity or low root density), the plant necessarily loses water. If the plant cannot adjust its root system to increase the water uptake, it may suffer from loss of turgor and not be able to grow normally. This situation will cause the plant to wilt. The environmental factors influencing evapotranspiration has been described in Chap. 3 (*Weather*).

8.2.7.1 Flow from Soil Through Root to the Vascular System

Roots are branched and have tortuous paths through the soil. Despite their complex geometry, any given segment of root can be treated as a cylinder to which water flows down a gradient of pressure in the soil water according to Darcy's law, to account for flow with cylindrical geometry:

$$v = K\frac{\mathrm{d}P}{\mathrm{d}x}, \tag{8.16}$$

where v is the flow rate ($\mathrm{m}^3\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}$), K is the hydraulic conductivity ($\mathrm{m}^2\ \mathrm{s}^1\ \mathrm{Pa}^{-1}$), and $\mathrm{d}P/\mathrm{d}x$ is the gradient in hydrostatic pressure ($\mathrm{Pa\ m}^{-1}$).

8.2.7.2 Longitudinal Flow in the Xylem

Xylem sap of a transpiring plant is usually under tension, with pressure typically in the range of -0.5 to -1.5 MPa in well-watered plant. The xylem usually offers little hydraulic resistance. The cohesive strength of water is so large that tensile failure does not occur.

8.2.7.3 From the Xylem to the Sub-Stomatal Cavities in the Leaf

In the past, the view was that the transpiration stream traveled through the apoplasm (cell walls and other compartments outside the cell membranes) to the sub-stomatal cavities, where water evaporated and diffused out of the leaf through the stomata. There is now compelling evidence that most of the water enters the symplasm (the interconnected cells) very soon after it leaves the vessels. As with radial flow in the roots, the passage of water across cell membranes results in a substantial fall in water potential.

8.2.7.4 Stomatal Control of Transpiration

The transpiration rate or the rate of flow out of the leaf is driven by diffusion as vapor through the stomata. It is controlled by the conductance of the stomata to water vapor according to:

$$E = g\frac{p_\mathrm{i} - p_\mathrm{o}}{p_\mathrm{a}}, \tag{8.17}$$

where p_i is the vapor pressure inside the leaf (Pa), p_o is the vapor pressure outside the leaf (Pa), p_a is the atmospheric pressure (Pa), and g is the conductance of the stomata ($\mathrm{mol\ m}^{-2}\ \mathrm{s}^{-1}$).

Stomatal conductance is the plant's main means of controlling transpiration rate. Shedding of leaf area is equally powerful means of controlling overall water use, and that is also strongly influenced by water relations.

Water potential influences transpiration rate by affecting the stomata, which close when water potential is low. Stomatal conductance is also influenced by many other factors, such as light level, concentration of carbon dioxide and hormonal levels, which are affected by adverse conditions in the soil such as salinity, dryness, and compaction.

8.2.8 ET Under Depleting Moisture

Evapotranspiration rate tends to decrease as the soil water content decreases. Actual evapotranspiration can be expressed as a function of crop characteristics, soil water availability, weather condition, and growth stage of crop, and is given by:

$$\mathrm{ET_a} = \int(\text{crop},\ \text{soil moisture},\ \text{weather parameter},\ \text{growth stage},\ldots) \tag{8.18}$$

Mathematically,

$$\mathrm{ET_a} = \mathrm{ET_0} \times K_\mathrm{c} \times K_\mathrm{s}, \tag{8.19}$$

where $\mathrm{ET_0}$ is the reference evapotranspiration (which depends on weather parameters), K_c is the crop coefficient, which depends on the crop type and crop growth stage, and K_s is the soil moisture stress factor *or* soil moisture coefficient *or* soil moisture adjustment coefficient. It depends on the state of soil moisture, the properties of soil, and meteorological conditions.

The actual evapotranspiration ($\mathrm{ET_a}$) varies with the soil water condition for particular crops, weather conditions, and crop growth stages. Different researchers have proposed different forms of equations to estimate actual evapotranspiration.

8.2.8.1 Woodhead's Equation

Woodhead (1976) used the following form of equation to calculate actual evapotranspiration from potential evapotranspiration under varying moisture condition:

$$\mathrm{ET_a} = \mathrm{ET_p}\left(1 - \frac{\mathrm{SMD}}{\mathrm{AW}}\right), \quad \text{when SMD} > \text{RC}$$

$$\mathrm{ET_a} = \mathrm{ET_p}, \qquad \text{when SMD} < \text{RC}, \tag{8.20}$$

where $\mathrm{ET_a}$ is the actual evapotranspiration, $\mathrm{ET_p}$ is the potential evapotranspiration, SMD is the soil moisture deficit, and RC is the root constant.

Nwabuzor (1988) obtained AW and RC value by parameter optimization of the soil moisture optimization model. Potential evapotranspiration can be obtained as:

$$\mathrm{ET_p} = \mathrm{ET_0} \times K_\mathrm{c},$$

where $\mathrm{ET_0}$ is the reference evapotranspiration and K_c is the crop coefficient.

8.2.8.2 Jensen Model

Jensen et al. (1971) assumed that the actual evapotranspiration is equal to potential evapotranspiration only at field capacity and then decreases in a logarithmic fashion, i.e.

$$\begin{gathered} \mathrm{ET_a} = \mathrm{ET_p} \times K_\mathrm{s} \\ K_\mathrm{s} = 1 \text{ when } \mathrm{SM} = \mathrm{FC} \\ K_\mathrm{s} = \frac{\ln(\mathrm{AW}+1)}{\ln(101)} \quad \text{when SM} < \mathrm{FC} \end{gathered} \tag{8.21}$$

where $\mathrm{ET_a}$ is the actual evapotranspiration, $\mathrm{ET_p}$ is the potential evapotranspiration, SM is the soil moisture status, FC is the moisture at field capacity, and AW is the percentage of available water (100 when the soil is at field capacity, and zero at wilting point).

AW depends on soil texture and is given by:

$$\mathrm{AW} = \left(\frac{\mathrm{SW} - \mathrm{PWP}}{\mathrm{FC} - \mathrm{PWP}}\right) \times 100 = \frac{\mathrm{SW} - \mathrm{PWP}}{\mathrm{ASM}_\mathrm{FC}} \times 100, \tag{8.22}$$

where PWP is the moisture content at permanent wilting point, $\mathrm{ASM_{FC}}$ is the MASM capacity (i.e., available moisture at field capacity). For a particular growth stage of any crop, AW should be calculated for the effective root zone depth of the crop.

8.2.8.3 Modified Jensen Model

Several researchers reported that transpiration rates fall below the estimated potential levels when the average value of soil water potential was reduced to -1 to -5 bars, depending on soil storage, root distribution, and potential transpiration rate (Seaton et al. 1977).

Rahman et al. (2007) and Ziaei and Seaskhah (2003) postulated that evapotranspiration takes place at potential rate from field capacity to a certain fraction of MASM and then decreases following logarithmic fashion as that of Jensen model:

$$\begin{aligned} \mathrm{ET_a} &= \mathrm{ET_p} \times K_\mathrm{s}, \\ K_\mathrm{s} &= 1, \quad \text{when} \quad \mathrm{ASM} \geq \mathrm{TF} \times \mathrm{ASM_{FC}}, \\ K_\mathrm{s} &= \frac{\ln(\mathrm{AW}+1)}{\ln(101)}, \quad \text{when} \quad \mathrm{ASM} < \mathrm{TF} \times \mathrm{ASM_{FC}}, \end{aligned} \tag{8.23}$$

where TF represents a threshold factor of MASM capacity, above which actual evapotranspiration takes place at potential rate. Rahman et al. (2007) optimized TF value as 0.85 in their study.

Experimentally, the K_s can be determined as:

$$K_\mathrm{s} = \frac{\mathrm{ET_a}}{\mathrm{ET_p}}. \tag{8.24}$$

Kang et al. (2000) found that K_s is highly related to soil water availability in a logarithmic function.

8.2.9 Workout Problems

Example 8.1. If the field capacity of a soil is 30% by volume, permanent wilting point is 15% by volume, calculate the plant available soil moisture storage capacity in 40 cm of soil depth.

Solution. We know, maximum plant available moisture storage in depth D,

$$d_\mathrm{masm} = \frac{\mathrm{FC} - \mathrm{WP}}{100} \times D.$$

Given FC = 30% (v/v), WP = 15% (v/v), D = 40 cm.
Putting the values in the above equation, $\mathrm{d_{masm}}$ = [(30–15)/100] × 40
= 6.0 cm (Ans.)

Example 8.2. A field soil having different distinct layers has the following soil-water coefficients:

	Thickness (cm)	FC (% vol.)	WP (% vol.)	Present state of moisture (% vol.)
Layer-1 (0–20 cm)	20	35	15	25
Layer-2 (20–40 cm)	20	40	18	27
Layer-3 (40–60 cm)	20	43	20	30

Maize crop is sown in the field. The effective root zone depth of the crop is 50 cm. Determine the following:

(a) Total maximum available soil water
(b) Total present available soil moisture

Solution.

(a)

We know, total MASM,

$$\mathrm{TMASM} = \sum_{i=1}^{n} \frac{(\mathrm{FC}_i - \mathrm{WP}_i)}{100} \times D_i$$

For layer-1, MASM ($L1$) = [(35–15)/100] × 20 = 4 cm
Similarly, MASM ($L2$) = 4.4 cm
MASM(L3) = 4.6 cm
Total = 4 + 4.4 + 4.6 = 13 cm
Thus, TMASM = 13 cm (Ans.)

(b)

$$\mathrm{TPASM} = \sum_{i=1}^{n} \frac{\theta_i - \theta_{\mathrm{PWP_I}}}{100} \times D_i.$$

For layer 1, PASM ($L1$) = [(25–15)/100] × 20 = 2 cm
PASM ($L2$) = 1.8
PASM ($L3$) = 2
Total = 5.8
Thus, TPASM = 5.8 cm (Ans.)

Example 8.3. In a SPAC, the soil water potential is −0.8 bar, leaf water potential is −400 bar. If the total resistance of flow in the soil-leaf pathway is 200 bar s mm^{-3}, find the steady transpiration rate.

Solution. We know,

$$E = \frac{\Psi_s - \Psi_l}{R},$$

Given $\Psi_s = -0.8$ bar, $\Psi_l = -400$ bar, $R = 200$ bar s mm^{-3}.
Putting the values in the above equation, $E = 1.996$ mm/s (Ans.)

Example 8.4. A shallow soil has initial soil water content of 42%. After 1,200 s, the moisture content became 32%. If the weighted mean diffusivity of the soil is 0.01 $\mathrm{m}^2\,\mathrm{s}^{-1}$, find the following:

(a) The evaporation rate
(b) Desorptivity

Solution. (a) We know, the evaporation rate, $e = (\theta_i - \theta_0)(\overline{D}/\pi t)^{1/2}$.

Given $\theta_i = 42\% = 42/100 = 0.42$, $\theta_0 = 32\% = 0.32$, $t = 1{,}200$ s, $D = 0.010.01\ \mathrm{m}^2\,\mathrm{s}^{-1}$.
Putting the values, $e = 0.000163$ m/s.
= 0.163 mm/s (Ans.)

(b) Desorptivity, $S_\mathrm{d} = 2(\theta_\mathrm{i} - \theta_0)(\overline{D}/\pi)^{1/2}$.

Putting the values, $S_\mathrm{d} = 0.01$ (Ans.)

Example 8.5. Assuming simple electrical circuit analogies in root water uptake, calculate transpiration rate from the following information:
Soil water potential = −0.6 bar
Leaf water potential = 10 bar
Resistance from soil to leaf pathway = 250 bar s mm^{-3}

Solution. Assuming simple electrical circuit analogies in root water uptake, transpiration rate

$$E = \frac{\Psi_\mathrm{s} - \Psi_\mathrm{l}}{R}.$$

Given $\theta_\mathrm{s} = -0.6$ bar, $\theta_\mathrm{l} = -450$ bar, $R = 250$ bar s mm^{-3}.
Putting the values in the above equation, $E = 1.797$ mm/s (Ans.)

Example 8.6. In a plant system, cumulative transpiration from a single leaf is 10 gm water, cumulative potential difference of soil and leaf over a particular time is 1,500 bar, and water content at the start and end of the time period are 20 and 12 gm, respectively. Find out the hydraulic conductance in the soil-leaf pathway.

Solution. We get,

$$W_{\mathrm{t}2} - W_{\mathrm{t}1} + \int E\mathrm{d}t = g\int(\Psi_\mathrm{s} - \Psi_\mathrm{l})\mathrm{d}t.$$

Given $W_{\mathrm{t}2} = 20$ gm, $W_{\mathrm{t}1} = 12$ gm, $\int E\mathrm{d}t = 10$ gm, $\int(\psi_\mathrm{s} - \psi_\mathrm{l})\mathrm{d}t = 1{,}500$.
Putting the above values in the above equation, $20 - 12 + 10 = g \times 1{,}500$
or $g = 0.001333$ gm bar^{-1} s^{-1} (Ans.)

Relevant Journals

- Journal of Experimental Botany
- Field Crops Research
- Crop Science
- Environmental and Experimental Botany
- Plant Physiology
- Advances in Plant Physiology
- Plant Science
- Agronomy Journal

- International Journal of Bioresearch
- Plant and Soil
- Transactions of the ASAE
- Agricultural Water Management
- Irrigation Science
- Hydrological Process

Questions

1. What do you mean by soil–plant–atmospheric continuum (SPAC)?
2. What is "water potential"? Describe the water potential of plant and soil.
3. Write down the principle of water movement in soil–plant–atmosphere pathways.
4. Explain the water pathways in higher plants with a neat sketch.
5. Briefly describe the different types of soil water constants.
6. Write short notes on: (a) Maximum plant available soil moisture, (b) Total maximum available soil moisture, (c) Total present available soil moisture, (d) Depletion of available soil moisture, (e) Air entry potential/suction.
7. What are the factors that affect plant response to water stress? Briefly discuss the effect of soil moisture stress on the plant system, growth, and yield.
8. What is the mechanism of injury of a plant under severe drought?
9. Describe the effect of soil moisture content on evaporation rate.
10. Discuss the implications of evaporation rate on soil water conservation practice.
11. Write down the equation expressing water uptake by a single root.
12. Deduce the equation for determining hydraulic conductivity through the soil–leaf pathway.
13. Write down the equation(s) for water flow through soil–plant–atmospheric continuum, and explain the terms.
14. What are the factors that affect ET? Narrate the different equations that express ET under varying soil moisture.
15. In a wheat field, the effective root zone depth is 60 cm at flowering stage. The soil has a uniform layer up to that depth. If the moisture content at field capacity and wilting point are 42 and 21%, and the current moisture content is 31%, determine the (a) total maximum available soil water, and (b) total present available soil moisture for the crop.
16. Assuming simple electrical circuit analogies in root water uptake, calculate the transpiration rate if soil water potential $= -0.75$ bar, leaf water potential $=$ 11.5 bar, and resistance from soil to leaf pathway $= 190$ bar s mm^{-3}.

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Chapter 9

Crop Water Requirement and Irrigation Scheduling

With increasing scarcity and growing competition for water, judicious use of water in agricultural sector will be necessary. This means that exact or correct amount and correct timing of application should be adopted. In addition, it will need more widespread adoption of deficit irrigation, especially in arid and semi-arid regions. Recent advances in new irrigation technologies will help to identify irrigation scheduling strategies that minimize water demand with minimal impacts on yields and yield quality, leading to improved food security. This chapter discusses the detail method for crop and irrigation water requirement and latest concepts of irrigation scheduling and strategies involved in irrigation scheduling. Numerous examples are incorporated to understand the procedure to calculate irrigation water requirement and irrigation scheduling. In addition, techniques for command area development are discussed along with sample illustrations of designing parameters for command area.

9.1 Crop Water Requirement

9.1.1 Definition

The amount of water needed to compensate the evapotranspiration loss from the crop field is termed as crop water requirement. The value of crop water requirement is identical to evapotranspiration. Crop water requirement varies with time and space, as the evapotranspirative demand varies with local climate and crop condition. Crop water requirement represents the evapotranspiration (ET) under ideal crop growth condition. The ET from a crop with insect and pest-affected condition and low population (crop density) will be different from that of a well-established and well-grown crop.

M.H. Ali, *Fundamentals of Irrigation and On-farm Water Management: Volume 1*,
DOI 10.1007/978-1-4419-6335-2_9, © Springer Science+Business Media, LLC 2010

9.1.2 Factors Affecting Crop Water Requirement

Weather and crop influence in determining water requirement for crop. The weather elements which influence crop evapotranspiration (ET), and the way they influence ET are described in Chap. 3 (Weather).

9.1.2.1 Crop Factor

Different crops use different amount of water during its growing period. Crop factors influencing crop water requirement include the following:

- Type of crop
- Cultivar/species
- Growing stage
- Leaf area
- Leaf type, stomatal behavior
- Root length, root density

Due to difference in growth pattern, different crops or even different cultivar of the same crop show different evapotranspiration demand. Length of crop duration has a direct effect on total water requirement. A wheat variety with maturity period of 150 days will use more water than 120 days variety. Crop planting time or the season has an impact on crop water demand due to differential energy pattern for evapotranspiration. Some crops are grown both in winter and summer/spring. Summer season crop will surely need more water than that of winter. Younger plants require less water than the mature one (Fig. 9.1). Besides, leaf area (evaporative surface) and stomatal closure behavior influence on ET. Under similar environmental condition, a plant having little leaf area and root system would

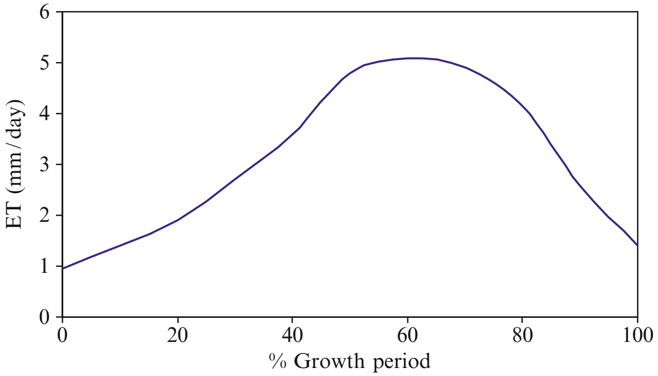

Fig. 9.1 Typical pattern of ET demand during the growth period of cereal crop

require much less water than a plant having higher leaf area and dense root system. In addition, crop population may influence ET demand – decrease in population will result in less ET.

Other factors determining total crop water requirement are growing season (winter or spring) and length of growing period (short or long duration crop cultivar).

9.1.3 Calculation/Estimation of Crop Water Requirement

Crop water requirement can be calculated from the climate and crop data. Crop water requirement for a given crop, *i*, for the whole growing season:

$$CWR_i = ET_i = \sum_{t=0}^{m} (ET_{0t} \times K_{ct}), \tag{9.1}$$

where $\mathrm{CWR_i}$ is the crop water requirement for the growing period, in mm, $\mathrm{ET_i}$ is the crop evapotranspiration for the growing period, in mm, *t* is the time interval in days, *m* is the days to physiological maturity from sowing or transplanting (total effective crop growth period), in numbers, ET_{0t} is the reference crop evapotranspiration of the location concern for the day *t*, in mm, and $K_{\mathrm{c}t}$ is the crop coefficient for the time *t* day.

Note: Actually, the crops do not need water up to the harvest date. Physiological maturity is the status of maturity after which the weight of the grains does not change/increase. Normally it reaches a week (7 days) ahead of traditional harvest time in cereals, and 3–5 days in pulses and oilseeds.

The methods for determining $\mathrm{ET_0}$ and K_c have been described in details in Chap. 7 (Field Water Balance). Crop water requirement for a particular growth stage (or period) of the crop can be calculated using the K_c for that growth stage (or period).

9.1.4 Difference Between Crop Water Requirement and Irrigation Water Requirement

Crop water requirement (CWR) and irrigation water requirement (IWR) can be best described with the following mathematical functions:

CWR = *f* (weather, crop)

IWR = *f* (weather, crop, soil, rainfall, irrigation method, depth to water-table *or* saturated layer)

Distinguishing characteristics of crop water requirement and irrigation water requirement are given below:

Crop water requirement	Irrigation water requirement
1. It is a function of weather and crop	1. It involves additional factors other than the weather and crop
2. Normally it is less than the irrigation water requirement	2. Normally it is higher than the crop water requirement
3. It is not a function of soil and irrigation method	3. It depends on soil type and irrigation method
4. It does not depend on rainfall (but on temperature and humidity)	4. Irrigation water requirement decreases if there is any rainfall
5. It is not a function of depth to water-table or saturated layer	5. It decreases with the contribution of upward flow from the water-table or saturated layer

Table 9.1 Water requirement of major crops

Crop	Water requirement (cm)	Crop	Water requirement (cm)
Alfalfa	150–160	Wheat (winter)	30–40
Bean	30–40	Wheat (spring)	40–55
Corn	50–70	Rice	110–160
Cotton	70–100	Sorghum /millet	40–50
Lentil	15–25	Soybean	30–50
Maize	40–60	Sugarcane	150–200
Groundnut	30–40	Sugar beet	75–90
Onion	30–40	Sunflower	40–55

Note: The typical values are based on average climatic condition (semi-arid to semi-humid), full irrigation strategy (no deficit), and flood irrigation method. The values for extreme climatic conditions will vary from this estimate (lower for cold climate and higher for dry climate). It may also vary depending on the season (some crops are grown in two seasons, winter and summer), time of transplanting or sowing, and duration of the crop (short duration cultivar will require less water than the long-duration one, and vice versa).

9.1.5 Water Requirement of Major Field Crops

Typical water requirement of some major crops are given in Table 9.1.

9.2 Irrigation Water Requirement

In the crop field, water is used in many pathways such as direct evaporation from soil and plant surfaces, transpiration through plant leaves, assimilation into the plant and plant fruits, and other beneficial uses such as salt leaching, crop cooling, and freeze protection. The beneficial uses are applicable for particular circumstances, but the other needs are essential for all conditions and they are governed by weather, soil and crop. Net irrigation water requirement is the quantity of water required for successful crop growth.

9.2.1 Factors Affecting Irrigation Requirement

The factors which influence crop water demand (ET demand), also influence the irrigation water demand. Weather, crop, and soil – all these three factors influence in determining water requirement for irrigation. Crop and weather factors influencing crop water demand have been described earlier.

9.2.1.1 Soil Factor

Soil factor does not affect irrigation demand directly (but a little by absorbing heat), but affect total water requirement by its storage and release properties of water. In addition to type of the soil, the organic matter content of the soil control a great deal to its storage and release properties. Seepage and percolation rate of sandy soil is much higher than that of the silt and clay soils. The rate of percolation follows the order: sandy soil > silt > clay soil. Hence, the total irrigation requirement during the crop growing season is higher in sandy soil than the clayey soil.

Other factors affecting irrigation water requirement include effective rainfall, water required for leaching of salt (leaching requirement), water required for land preparation or land soaking, etc. Estimation of these components is described below.

9.2.2 Components of Total Water Requirement for Irrigation

Total irrigation water requirement is the amount of water required during the cropping period for successful crop cultivation. Total irrigation water requirement of a crop may be consisting of the following components:

- Water for land preparation (as pre-sowing irrigation for dry-land crops)
- Water for land soaking (specially for rice)
- Crop water demand (includes ET and seepage and percolation)
- Water for leaching requirement (specially in saline soil)
- Water for special use such as crop cooling, freeze protection

For each crop *or* for each area, all of the above items may not essential. For dry-land crops, a pre-sowing irrigation may be needed, while for rice crop, a large amount of water is needed for land soaking. Water for leaching is needed for saline soil to lower the salinity level.

9.2.2.1 Water Requirement for Land Soaking

This is the water required to soak the land prior to the initial breaking of the soil, either by plowing or by any other means. The amount of water necessary for land soaking depends on the residual or existing soil moisture, soil texture, depth of soil to be saturated or depth to the hardpan, the type of clay minerals, seepage and percolation losses, evaporation from standing water, amount of rainfall occurring at the time, and application efficiency.

This is expressed as:

$$\mathrm{WR_{LS}} = \frac{W_s + C \times \mathrm{ET_0} + P - R_e}{E_a} \tag{9.2}$$

where $\mathrm{WR_{LS}}$ is the depth of irrigation water required for land soaking (mm), W_s is the depth of water required to saturate the soil (mm), $\mathrm{ET_0}$ is the reference evapotranspiration during the time of soil saturation (mm), C is the evaporation coefficient equating reference evapotranspiration to evaporation rate. The value of C is about 0.9.

P is the deep percolation loss during the soil saturation (mm), R_e is the effective rainfall during the period (mm), and E_a is the application efficiency.

9.2.2.2 Water Requirement for Land Preparation

This is the irrigation water required to maintain the saturation condition of the soil from the first breaking of the soil to seedling or transplanting. This water is required to replace evaporation, percolation, and application losses and includes the addition of water depth to suppress weeds or soften soil clods. This is expressed by the equation:

$$\mathrm{WR_{LP}} = D_s + C \times \mathrm{ET_0} + P - R_e \tag{9.3}$$

where $D_s$water depth for submergence (mm).

Considering application efficiency,

$$\mathrm{WR_{LP}} = \frac{D_s + C \times \mathrm{ET_0} + P - R_e}{E_a}$$

9.2.2.3 Water for Leaching

This is the water required to leach the excess salt out of the root zone. It is the extra amount in addition to evapotranspiration. The details regarding leaching and salinity management have been described in Vol. 2 (Salinity management). The fraction of irrigation water required for leaching (termed as leaching fraction) can be calculated using the following formula (Rhoades 1974):

$$\mathrm{LR} = \mathrm{EC_w}/(5\mathrm{EC_t} - \mathrm{EC_w}) \tag{9.4}$$

where EC_w is salinity of the applied irrigation water, and EC_t is the threshold salinity (average soil salinity tolerated by the crop).

The total depth of water for a particular season or period that needs to be applied to meet both the crop demand and leaching requirement can be calculated as (Ayers and Westcot 1985):

$$AW = ET/(1 - LR) \tag{9.5}$$

where AW is the depth of applied water (cm/season), ET is the total seasonal demand (cm/season), and LR is the leaching requirement, expressed as fraction (leaching fraction, LF).

9.2.2.4 Net Irrigation Water Requirement for Normal Growth Period (W_{nci})

For rice, this is the irrigation requirement immediately following transplanting (or a week after direct seeding) until the start of terminal drainage which is usually referred to as the normal irrigation period. For other crops, this requirement starts as soon as planting begins and last as long as water is needed by the crop. It is expressed by the equation:

$$IWR_{nc} = \sum [(K_c \times ET_0) + P - (R_e + GW_c)] \tag{9.6}$$

where IWR_{nc} is the net irrigation requirement for normal growth period (from sowing/transplanting to last watering, i.e., excluding land preparation and pre-sowing irrigation) (mm), GW_c is the groundwater contribution during the period (mm), P is the deep percolation loss during the period concerned (mm), and K_c, ET_0, R_e are defined earlier.

The procedure for determining K_c and GW_c have been described in Chap. 7.

9.2.3 Total Irrigation Water Requirement

9.2.3.1 Total Net Irrigation Water Requirement

It is the water required for normal field crop irrigation plus water required for special purposes as discussed above, that is:

$$NIWR = WR_{LS} + WR_{LP} + WR_{nc} + WR_L \tag{9.7}$$

where NIWRis the total net irrigation requirement for successful cultivation of a crop (mm), WR_{LS} is the depth of water required for land soaking (mm), WR_{LP} is the depth of water required for land preparation (mm), WR_{nc} is the depth of water required for crop ET demand (mm), and WR_L is the depth of water required for leaching (mm).

For all crops and for all conditions, all of the above components may not necessary. Only the relevant components should be added together.

9.2.3.2 Gross Irrigation Water Requirement (W_{gross})

During delivery of water in the crop field, some losses occur such as inefficiencies in conveyance system, evaporation and wind drift (specially for sprinkler irrigation). Besides, surface runoff and percolation below root zone may occur from the field plot. For these reasons, the water that should be pumped to supply the crop water requirement should be higher than the actual (net) crop water requirement. The above losses can be minimized through proper management practices, but cannot be eliminated completely. These points should be considered during determination of total irrigation water requirement.

Gross water requirement is the water required for irrigation considering field application loss and conveyance loss. That is

Gross irrigation requirement,

$$\mathrm{GIWR} = \frac{\mathrm{NIWR}}{E_a \times E_c} \tag{9.8}$$

where E_c is the field conveyance efficiency, E_a is the field application efficiency.

In summary, the following steps may be followed for the calculation of irrigation water requirement:

- Identify the climatic zone and/or agro-ecological zone of the project area
- Select the appropriate crop/cropping pattern for the area
- Collect long-term climatic data and the soil information
- Calculate reference evapotranspiration for the crop period
- Collect crop coefficient value from the literature or from similar crops/varieties, if available
- Calculate crop evapotranspiration (ET_c) (i.e., crop water demand)
- Calculate other special water requirement, if any (e.g., land preparation/soaking, leaching requirement for salt balance)
- Determine total water requirement (net water requirement, NIR)
- Estimate overall water conveyance efficiency (E_c) and water application efficiency (E_a)
- Determine total irrigation water requirement (gross irrigation water requirement) by dividing the NIR by E_c and E_a.

For a particular irrigation event, irrigation water requirement based on soil moisture deficit is

$$\mathrm{NIWR_m} = \frac{\sum_{i=1}^{n} (\mathrm{FC}_i - \mathrm{SM}_i) \times d_i}{100(1 - \mathrm{LF})} \tag{9.9}$$

where FC_i is the field capacity (water holding capacity) of soil of i layer, in percent volume, SM_i is the present soil moisture content, in percent volume, d is the depth of i layer, in cm, LF is the leaching fraction.

If leaching is not required, LF = 0.

Then,

$$\mathrm{GIWR_m} = \frac{\mathrm{NIWR_m}}{E_\mathrm{a} \times E_\mathrm{c}} \tag{9.10}$$

9.2.4 Sample Examples on Calculation of Irrigation Water Requirement

Example 9.1. The following information is available for a land:

- Depth of water required to saturate 20 cm soil = 6 cm
- Daily reference evapotranspiration = 5 mm
- Time from water application to deplete field capacity = 6 h
- Deep percolation loss during soil saturation = 4 mm
- Rainfall during the period = 0

Determine the irrigation water requirement for land soaking.

Solution Irrigation water requirement for land soaking, $\mathrm{IWR_{ls}} = (W_\mathrm{s} + C \times \mathrm{ET_0} + P - R_\mathrm{e})/(E_\mathrm{a} \times E_\mathrm{c})$.
Given,

$W_\mathrm{s} = 6$ cm $= 60$ mm,
$P = 4$ mm,
$R = 0$,
$\mathrm{ET_0}$/day = 5 mm,
$\mathrm{ET_0}$/6 h = 2.5 mm,
$E_\mathrm{a} = 95\% = 0.95$,
$E_\mathrm{c} = 80\% = 0.8$.

Assume coefficient for relating $\mathrm{ET_0}$ to actual evaporation, $C = 0.95$, and putting these values in above equation, we get, $\mathrm{IWR_{ls}} = 87.3$ mm (Ans.)

Example 9.2. For winter wheat crop grown in spring, the following information is gathered for a particular growth phase:

Reference evapotranspiration for the growth phase = 30 mm,
Crop coefficient for that phase = 1.0,

Deep percolation for water application = 4 mm,
Groundwater contribution = 0.

Find:

(a) Net irrigation required
(b) Gross irrigation required, if application efficiency = 85%, and conveyance efficiency = 75%

Solution Given,

ET0 = 30 mm,
$K_c = 1.0$.
$P = 4$ mm,
$R_e = 5$ mm,
$GW_c = 0$,
$E_a = 85\% = 0.85$,
$E_c = 70\% = 0.7$.

(a) We know, net irrigation req., $WR_{nc} = (K_c \times ET_0) + P - (R_e + GW_c)$.

Putting the value, $WR_c = (1 \times 30) + 4 - (5 + 0) = 29$ mm (Ans.)

(b) Gross irrigation water reqquirement, $GIWR = WR_c/(E_a \times E_c) = 29/(0.85 \times 0.7) = 45.5$ mm (Ans.)

9.3 Basics of Irrigation Scheduling

The availability of water is a major factor limiting crop production in most regions of the world. Inadequate and/or non-uniform distribution of rainfall, low water-holding capacity of most soils, and sensitivity of many crops to water stress and consequent economic yield loss result in irrigation application to crop. The objective of irrigation is to maintain a favorable plant water environment for proper growth. The irrigation water should be applied in such a manner that it is most effectively and efficiently used by the plants.

9.3.1 Concept of Scheduling

The problem of irrigation consists of when to irrigate, and how much to irrigate. Efficient water use depends on timely application of water at right amount at right time with right way or method. Irrigation scheduling means when to irrigate and how much water to apply in crop field. In other words, irrigation scheduling is the decision of when and how much water to be applied in a crop field. The objectives of irrigation scheduling are to maximize yield, irrigation effectiveness/efficiency, and crop quality by applying the exact amount of water needed by the crop (or to replenish the soil moisture to the desired level).

Proper irrigation scheduling minimizes the following:

- Yield reduction
- Wastage of water (deep percolation loss and runoff) and energy
- Irrigation cost
- Excess groundwater withdrawal (aquifer exploitation)
- Nutrient leaching
- Pollution of surface and groundwater by agro-chemicals
- Drainage requirement
- Water-logging and salinity hazard
- Environmental and health hazard (disease)

On the other hand, irrigation scheduling saves water, energy, and labor. Irrigation scheduling maximizes yield response to other management practices (e.g., fertilizer application). It also keeps the water environment clean and safe. The decision in irrigation scheduling thus involve optimally managing the existing resources (water, labor, and equipment).

9.3.2 Indicators of Irrigation Need Assessment

To determine the need of irrigation (i.e., time of irrigation), some sorts of indicators or criteria should be established. Commonly used indicators or symptoms are as follows:

- Plant leaf appearance
- Soil moisture status (hand-feel or instrumental)
- Soil-water potential
- Leaf-water potential
- Leaf temeprature.

As the objective of irrigation is to maintain a favourable plant water environment for crop growth, the plants themselves may be the best indicator of irrigation need. But the problem is that, the time when the crop shows such symptom (wilting symptom), the yield reduction may already have occurred. Due to this problem, the irrigations are frequently scheduled based on soil moisture or soil-water potential. Leaf-water indicator is rarely used in practice, but in research stations. Sometimes, combination of the above methods is used (such as plant appearance and soil moisture).

9.3.3 Factors Affecting Irrigation Scheduling

Irrigation scheduling is complicated due to the fact that irrigation timing and amount of water to be applied are not independent of each other. Both depend on other numerous factors. Knowledge of soil, water, plant, and their inter-relationships is essential for proper irrigation scheduling. When to irrigate depends on water use rate by the plant (depends on weather), total available soil moisture within the plant's root zone (depends on soil and plant factor), other form of water source (if any, e.g., rainfall, snow, capillary rise from groundwater or saturated zone), maximum allowable or management allowable soil moisture depletion level, plant's response to soil moisture deficit, other form of abiotic stress (if any, e.g., salinity stress), etc. How much water to apply depends on moisture storage capacity of the soil, present level of moisture at which irrigation is to be started, root zone depth (depends on plant factor), any other sink of water other than plant (if any, e.g., salt leaching), depth to water-table (risk of rising), sub-surface drainage facility (if any), efficiency of the irrigation system, etc.

Thus, the factors influencing irrigation scheduling include the following:

- Goal and/or strategy of irrigation
- Soil factor
- Plant or crop factor
- Crop response to water stress
- Weather factor
- Water-table depth
- Water quality
- Design of existing irrigation system (or the cost of proposed irrigation system)
- Volume of soil to be irrigated/effective root zone depth
- Cultural/management practices
- Cost/economic factor

9.3.3.1 Goal/Strategy of Irrigation

Both the time and amount of irrigation is influenced by the goal of irrigation. The possible irrigation goals may be as follows:

- Maximizing yield per unit of land
- Maximizing yield per unit of water (i.e., maximizing water productivity)
- Maximizing yield per unit of energy
- Profit maximizing

Irrigation scheduling strategy for different goals may differ from each other. Based on the irrigator's goal, criteria for irrigation timing and amount are fixed up. However, the irrigation goal can be affected by existing land, labor and/or water resource conditions, such as the following:

- Water-limiting condition
- Land-limiting condition
- Abundant water and land condition
- Labour-limiting condition

Water-limiting condition is one in which water is limited but the land is abundant, and additional land can be brought under irrigation if extra water is available. Land-limiting condition is one in which land is limited but water is abundant. Under water-limiting condition, irrigation scheduling strategy may be such that yield is maximized per unit of water (i.e., maximize water use efficiency or water productivity), while under land-limiting condition the strategy may be producing maximum yield per unit of land.

If the goal is profit maximizing, irrigation scheduling should be such that the net profit (total gross income minus total cost) would be maximum (under both land- and water-limiting condition). Profit maximization occurs at the point in which the marginal benefit of irrigation equals its marginal cost.

In areas with abundant land and water, the aim should be in producing optimum yields without incurring wasteful losses of water. The optimum irrigation amount occurs when the increase in yield of the last unit of water applied becomes very low.

In addition, irrigation scheduling may be motivated by the type and value of the crop. High value crops may be irrigated frequently, and the vice versa.

Thus, it is revealed that, when to irrigate and how much to irrigate depends on the strategy selected by the irrigator based on the prevailing resource condition (water, land, labour, and capital) and the type and value of the crop.

9.3.3.2 Soil Factor

Total plant available water (PAW) is the water between field capacity and wilting point (storage capacity) within the root zone soil. This storage rate varies with soil textural class and to some extent with organic matter content. Thus different soil types have different PAW. The loam and clay soils have higher PAW than the sandy one. This factor should be considered in irrigation scheduling. The capacity of the soil to preserve plant available water is determined by multiplying soil's water-holding capacity by the crop root depth.

Plant factor

The following aspects of plant should be considered during irrigation scheduling:

- Effective root zone depth
- Drought sensitivity
- Growth stage
- Water use rate

Plants do not extract water uniformly from the whole rooting depth. Rooting pattern and depth vary from plant-type to plant-type. It also varies with crop development or growth stage. Effective root zone depth (ERD) is the depth within which most of the plant roots ($\sim$80%) are concentrated. The plants extract most of its water from this zone. Both the maximum root depth and effective root depth reaches its maximum value during flowering stage of the crop. Extractable moisture increases during the season as roots grow deeper, thus enlarging the storage reservoir. Changes in rooting depth will affect the total amount of water available to the crop and the amount of water applied during an irrigation. The effective root depth should be considered in computing total plant available water.

Different crop species have different drought tolerance (or sensitivity) capacity. Some crops are most sensitive to water deficit, hence requiring more frequent irrigation. Some are capable of drought tolerance, hence requiring less frequent irrigation.

Water absorption rate or use rate by the plant varies with plant age or growth stage. With the increase in leaf area, more water is demanded, reaching to its maximum at flowering stage. At the ripening stage, water demand is less. Thus, irrigation scheduling should be based on this consideration.

9.3.3.3 Weather Factor

Rate of water withdrawn by plant depends on the atmospheric water demand. The higher the evapotranspirative demand, the lower the irrigation interval (and consequently higher irrigation frequency) for a particular water storage, and vice versa. Consideration of rainfall should be taken into account in semi-arid or humid areas. In humid areas, where there is a high probability of rainfall, irrigations should be scheduled according to the expected rainfall (by different levels of probability, or by using historical average data, or by short-term weather forecasts).

9.3.3.4 Water-Table Depth

In areas with shallow water-table or saturated layer, the upward capillary flow from the water-table should be considered to meet the crop water requirements. Up to about 40–50% of the crop water demand can be met through capillary upflow.

9.3.3.5 Design of the Existing Irrigation System

Irrigation scheduling program should be based on the type of existing irrigation system (flood, drip, or sprinkler). The sprinkler should have frequent irrigation with small amount while the flood may have higher depth but longer interval. In case of new installation, the cost of irrigation system should be taken into account.

9.3.3.6 Volume of Soil to Be Irrigated

The irrigation system, and consequently the frequency and amount (i.e., scheduling) should be based on the depth of soil to be wetted. If the rooting depth is low (and consequently lower soil volume), sprinkler system is more appropriate than other systems. This, in turn, affect the frequency and depth of irrigation.

9.3.3.7 Cultural Management

If much is used, irrigation requirement will be lower, and thus affect on scheduling. Similarly, if intercropping is practiced, it will motivate the irrigation practice.

9.3.3.8 Economic Factor

Irrigation scheduling is influenced by cost of the system (capital requirement) and the net economic return. If the crop is high valued and the net return is high, the higher investment in irrigation system will be accepted by the growers.

9.3.4 Common Irrigation Scheduling Methods Used by the Farmers

Many methods of scheduling irrigations are used by the farmers. These methods include the following:

- Crop observation
- "Feeling" the soil
- Application of irrigation weekly to bring the water to a set amount (say, 5–7 cm for rice)
- Rotation basis (provision of irrigation scheme or pump owner)
- Pan evaporation observation
- Check book method/irrigation calendar

In some areas, irrigations are set up on rotation basis with constant intervals and either constant or variable amounts, but generally disregarding annual climatic variation. Such systems inherently result in low irrigation efficiencies and low yield potentials. Similarly, continuous flow systems are inefficient because evapotranspiration and precipitation are not uniform during the season.

Although both timing and amount of water applied affect irrigation efficiency, timing has the greatest effect on crop yield and quality because at some crop growth stages, excessive soil moisture stress caused by a delayed irrigation and inadequate irrigation, can irreversibly reduce the potential yield and quality of the crop or both. When stress symptoms are visible, damage generally has already occurred or will occur by the time the field can be irrigated.

9.3.5 Advanced Irrigation Scheduling Approaches

Available advance methods or approaches for irrigation scheduling are as follows:

1. Climatological approach
2. Pan evaporation
3. Crop growth stage basis
4. Soil moisture basis
5. Deficit irrigation concept
6. Soil-water potential

7. Leaf water potential
8. Stress-day index
9. Irrigation calendar
10. Check-book or soil-moisture balance approach
11. Modeling approach
12. Real-time irrigation scheduling

More direct methods of scheduling irrigation require the use of instruments that measure parameters related to soil moisture content. The use of soil moisture blocks to schedule irrigations has been advocated but not widely practised. Blocks are generally better suited for crops that can stand a higher soil moisture stress and for soils with low salt concentrations. Gravimetric determination of existing soil moisture gives a direct indication of moisture use, but tedious. Estimated consumptive use rates coupled with gravimetric determinations may provide an excellent basis for predicting irrigations.

9.3.6 Factors Influencing Choice of Irrigation Scheduling Method

Methods or approaches of irrigation scheduling are dependent on various inputs. Each of the methods has some limitations. Limitations and input requirements of each approach/technique are important in the selection of appropriate scheduling method. Appropriate irrigation scheduling method should be based on the technology level at the farm/locality concerned, conditions of water availability and water supply, financial ability of the farmer, market value of the product and/or alternate use of water.

9.4 Description of Different Irrigation Scheduling Methods or Approaches

9.4.1 Climatic Approach/Evapotranspiration Basis

The potential advantages of scheduling irrigations using climatic data have been advocated by many researchers. Penman (1952), for example, analyzed this approach in 1952 as others have since then.

According to this concept, crop water demand (ET) is calculated using different available mathematical equations (described in Chap. 7, “Field Water Balance”). With this approach, evapotranspiration (ET) may be calculated in two ways: using long-term historical average weather data for the crop period (or the particular growth stage) in advance, or based on current weather condition assuming that weather will be similar for the next intended period. Irrigation is applied with equal to ET amount, or a fraction or multiples of ET. For a particular crop and for a particular location, optimum amount is to be established for optimum and/or economic yield.

Fischbach and Somerhalder (1974) used the evapotranspiration rate of the plant to determine irrigation needs. Hill and Guron (1973) applied the amount of water equivalent to 1.2, 1.1, 0.75, 0.50, 0.40 of the peak ET rate of maize at fixed intervals and obtained higher yields with increasing amount of water. Fischbach and Somerhalde (1974) applied amounts equivalent to the daily ET peak (7.52 mm/day) and 0.75, 0.50, and 0.33 of the daily peak at frequencies of 1.5 to 7 days and reported that the amount of water equivalent to 0.5 of the peak ET rate gave the highest yield for all frequencies tested. The use of ET approach demands that the evapotranspiration rate be known. In determining ET, historical average of weather data is normally used; which may be reliable estimate in some cases, but may be different in some cases, especially in rapid fluctuating weather condition.

9.4.1.1 Shortcomings

A number of weather parameters are needed to determine ET value. It is difficult to obtain these data at the site/field, and it is costly. Besides, it requires expert technical man to have the accurate data. In using historical data, the uncertainty exist that, the weather condition in the future may deviate substantially from the past.

9.4.2 Pan Evaporation

The amount of pan evaporation is a combined effect of weather parameters. If the pan can be designed appropriately and placed in a representative place, it may provide reasonable estimate of evaporation from free water surface. It may also be termed a climatological approach.

Open pan evaporation may be used to estimate evapotranspiration and irrigation requirement of field crops, provided a relationship between evapotranspiration and open pan evaporation (the coefficient relating pan evaporation to crop water requirement) has been established for a given area. Irrigation is applied simply equal to the cumulative pan evaporation at several days interval. This interval depends on weather condition and crop type. It may be 3, 5, 7, 10, or 15 days, for example.

Sometimes irrigation is applied relating applied irrigation amount (IW) to cumulative pan evaporation (CPE), that is, according to the ratio of IW to CPE [IW/CPE ratio], where CPE is the cumulative open pan evaporation minus effective rainfall. Different ratios of IW/CPE have been suggested by the researchers for different crops. The choice of such ratio of IW/CPE is a matter of selection for desired yield level. Irrigation is applied when a pre-determined ratio of IW/CPE is reached. This approach requires a little more alert and technical calculation compared to only pan evaporation basis. The co-efficient relating pan evaporation to crop irrigation water requirement must be soil type and location specific and the co-efficient should be determined under a high level of management (Ali and Talukder 2001).

Evaporation from a standard open pan evaporimeter takes into account the effects of advective energy along with other parameters of the climate. Thus, it may be inferred that the pan evaporimeter may serve as a good guide for scheduling irrigation. This concept is simple and needs no technical hand and no sophisticated instrument. The record of pan should be taken daily or at several days interval. The pan may be locally made. The cost of a pan is within the economic ability of the farmers.

Irrigation based on pan evaporation is widely used in many places of the world both at research and farm level. In some places, irrigation is applied equally to cumulative pan evaporation at several days interval.

From the above discussions, it is revealed that irrigation based on pan evaporation is an easy and simplest way to irrigate the crop for the resource poor farmers. Although the actual needs may slightly deviate from the amount of pan evaporation, once the ratio is established by the researchers for the specific crop for the location concerned, there is no problem to apply this approach.

9.4.2.1 Shortcoming

In IW/CPE approach, the frequency of irrigation varies with the initial depth of irrigation water (IW). Rafey et al. (1978) found ideal IW/CPE ratio of 0.75 for wheat when the depth of irrigation was 8 cm whereas when the depth of irrigation was reduced to 5 cm, the suitable IW/CPE ratio was found to be 0.9. Taking the initial depth of irrigation without considering soil moisture status, may result over or under irrigation.

9.4.3 Crop Growth Stage Basis

According to this concept, irrigation is applied at different physiological phases (or growth stages) of the crop. To implement the stage-based concept, different physiological/development stages of the concerned crop (s) are to be identified.

Water stress, as with most other forms of stress, tends to hasten the rate of plant development. This reaction is probably an expression of plant survival. Generally water stress reduces biological yield, but it does not always decreases economic yield; in fact in some cases it may increase it. The effects of stress depend on its intensity and duration and also on the development stage of the plant (Ali et al. 2007). This point should be taken into consideration while scheduling deficit irrigation according to this approach.

A fixed schedule based on the development stage of the crop may result in over or under irrigation because water is applied without considering the soil water content or water use by the crop (atmospheric water demand). The number of irrigation at a particular stage should be prescribed based on the evapotranspirative demand of the crop at the location concerned and length of the particular stage. One or more irrigation may be needed at each stage.

9.4.3.1 Advantage

Irrigation based on different physiological growth stages is relatively easy to implement.

9.4.3.2 Shortcomings

Irrigation at a particular stage may be wasteful because of rainfall or residual soil moisture from the previous irrigation, and lower atmospheric demand. In the same way, crop may suffer from water deficit due to higher atmospheric demand and accelerated physiological processes, if only one irrigation is applied at each stage.

9.4.4 Soil Moisture Basis

This approach relates irrigation scheduling with the available water depleted from the crop root zone soil. Irrigation is applied (i.e., moisture is refilled) when the soil moisture reaches (i.e., lowers or depleted) to a pre-selected level. The refill point is established using two criteria: (1) at what depletion should irrigation result in optimum yields, and (2) at what depletion would the crop show water stress? The amount of water available to a crop and the water use rate by that crop are required to schedule irrigation correctly. For optimum yield of the crop, efficient water use and water saving; refill point for individual growth stages may be needed.

Allowable soil-water depletion varies with soil and crop conditions. It may also vary with management objective (e.g., potential yield or economic yield). The above two points should be determined experimentally for individual crops and major soil groups. After establishing these two points, irrigation may be suggested monitoring the soil moisture. The water required to fill up to field capacity is the irrigation amount.

The soil moisture can be monitored using a variety of tools and instruments, which are described in details in Chap. 4 (Soil).

9.4.4.1 Irrigation Scheduling Using Neutron Probe

The neutron probe measurements of soil moisture depletion can be used to determine the values of transient water use by plants as well as transient water loss by drainage. Correct irrigation scheduling by use of the neutron probe requires identification of the refill point (the point at which irrigation should occur) and periodic moisture measurements by the neutron probe. Periodic soil moisture measurement with the neutron probe will yield both the ambient soil moisture content and the rate of water use by the particular crop. A simple graph showing soil-water content plotted vs. time, with the refill point indicated, will yield a visual means of forecasting accurately the date of the next irrigation.

In the literature, ranges of information are available on allowable moisture depletion for cereal crops. But sensitivity to water deficit is dependent on soil, weather, plant type (architecture, physiology), and genotype. Thus information about allowable soil moisture depletion for each crop under different soil types and agro-climatic conditions are necessary. In a study using three moisture regimes (Irrigation at 20, 40, and 60% depletion of available soil moisture (ASM)), Rathore et al. (1978) observed that irrigation applied at 60% ASM was the best for wheat, the consumptive use of water for this level of moisture regime was 36.25 cm.

9.4.4.2 Advantage

It is more scientific and reliable approach. Irrigation water may be saved using this approach.

9.4.4.3 Shortcoming

Although scheduling of irrigation based on soil water depletion is more scientific, it is difficult to ascertain the field soil moisture in the root zone at farmer's level. This approach is only feasible where soil moisture monitoring facilities are available. This method is not practicable on large scale. In addition, limitations/drawbacks of individual instruments to estimate soil moisture pose restricted use of this approach.

9.4.5 Deficit Irrigation

9.4.5.1 Background

All growth stages of crops are not identical in their susceptibility to any moisture deficit. The sensitivity of various growth stages to water stress have been variable, depending upon variety, plant types (tall or dwarf), and maturity period. Generally water stress reduces biological yield, but it does not always decreases economic yield; in fact, in some cases it may increase it. In water-scarce areas, water (not land) is the primary limiting factor to improve agricultural production. Accordingly, maximizing yield per unit of water, and not yield per unit of land, is a more viable objective for on-farm water management. Scarce water now used for full irrigation may be revised for improved water productivity.

9.4.5.2 Concept and Definition

Deficit evapotranspiration is among the techniques of increasing effective use of water. Crops are exposed to water stress up to certain degree either throughout the entire growth season or at certain growth stages. The main approach in deficit irrigation practice is to increase crop water productivity by eliminating those irrigations with the least impact on crop yield.

By definition, deficit irrigation is the deliberate and systematic under-irrigation of a crop (English 1990). Simply speaking, deficit irrigation means less application of water than a plant has the potential to use or would normally use. Sometimes it is referred to as partial irrigation. Under deficit irrigation, crops are deliberately allowed to sustain some water deficit and yield reduction.

The concept of deficit irrigation is based on the assumption that in field crops, imposing water stress at specific growth stages may not cause significant yield reduction and irrigation in these stages can be ignored, which will save substantial amount of irrigation water. Although yields will be reduced under deficit irrigation, the reduction in irrigation costs and the opportunity costs of water may be more than the compensation for lower yields. When the amount of land under irrigation is constrained by limited water availability, the economic returns to water will be maximized by reducing the depth of water applied and increasing the area of land under irrigation.

In essence, deficit irrigation implies an optimization strategy in which irrigation is applied during drought-sensitive growth stages of the crop. A decision to practice deficit irrigation implies a willingness to accept reduced yields in exchange for increased net farm income. The specific objective is to optimize yield and income by allocating water to the most sensitive crop stages. Correct application of deficit irrigation requires a thorough assessment of the economic impact of the yield reduction caused by deficit irrigation.

9.4.5.3 Need of Deficit Irrigation

Deficit irrigation (DI) is needed and/or practiced where essential resources such as water, capital, energy, and/or labor are scarce and limited. The potential benefits of deficit irrigation may be achieved from the following factors:

1. Increased irrigation efficiency
2. Reduced costs of irrigation
3. The opportunity costs of water

As the efficiency and profit are both increased with reduced levels of applied water, the net income per unit of applied water is increased. If the water saved by reducing the depth of irrigation is then used to bring additional land under irrigation (with the same incremental profit per unit of land, or even something less), the total farm profit is still more. The net income from the additional land represents the opportunity cost of water. The term "opportunity cost" has been described in detail in Chap. 11 (Economic in Irrigation). The potential advantages of deficit irrigation appear to be quite significant, particularly in a water limiting situations, and the associated risks may be quite acceptable.

9.4.5.4 Modes of Deficit Irrigation

Deficit irrigation has been practiced in different modes or ways. These are:

1. *Increasing interval between irrigations*: The irrigation frequencies are reduced by increasing the days of interval between successive irrigations.
2. *Omitting irrigation during certain growth stages*: Irrigation can be omitted during the stage or stages which are less sensitive to moisture deficit.
3. Providing a part of evapotranspiration (ET) demand (i.e., reducing irrigation depth)
4. Wetting partial root zone
5. Wetting alternate furrows
6. Allowing root zone soil-water depletion to a particular level
7. Allowing root zone soil-water depletion to reach a particular level of leaf water potential
8. Any combination of the above

9.4.5.5 Procedure for Adopting Deficit Irrigation

The relationship between the crop water stress and yield is very important in scheduling deficit irrigation. In other words, to utilize this approach in practice, sensitivity of different growth stages to water stress (single stress in a particular stage, or alternate stress in several stages, or stress at a stretch) should be determined for each crop at each agro-ecological and/or geo-hydrological situation. After establishing the sensitivity of growth stages, irrigation can be avoided at less sensitive stage(s); and this saved water can be used to irrigate more cropped area or other valuable crops.

9.4.5.6 Risk/Uncertainty, Advantage, and Constraint of Deficit Irrigation

Risk

The uncertainty associated with this type of irrigation system from the fact that the cost of the water used and the yield function are not precisely known. If precisely known, it would be a simple matter to choose an optimum level of water use. The yield function tends to be uncertain due to the difficulty in estimating the water losses by inefficient application, by deep percolation, and by surface and subsurface runoff. Deficit irrigation may require modification of some cultural practices which may include: lower plant densities, flexible planting dates and selection of shorter duration crops.

Advantages

- Deficit irrigation maximizes productivity of water (also termed as “water use efficiency”).
- In water limiting areas, this practice is economically more profitable than maximizing yield per unit area.
- It creates less humid environment around the crop than full irrigation, thus decreasing the risk of fungal and associated diseases.
- Increases quality of the yield (protein content, sugar content, grain size, etc.).
- Reduce nutrient loss through leaching, thus require less fertilizer application and improve groundwater quality.
- Increases assimilate partitioning to grain from vegetative parts.
- Reduces crop cycle length (i.e., crop period), thus facilitates to increase cropping intensity.

Constraints

Along with the above advantages, deficit irrigation (DI) entails a number of constraints. The following conditions should be met to use DI:

- Yield response to water deficit or drought stress at different growth stages should be studied carefully.
- Water should be available at sensitive growth stages.
- In saline area, leaching of salts from the root zone is lower under DI than under full irrigation.

9.4.5.7 Reasons/Mechanisms for Increased Water Productivity Under Deficit Irrigation

- Water loss due to evaporation is reduced.
- Water loss through transpiration is also reduced.
- Soil-moisture extraction from deeper layer is increased.
- Water is used most efficiently within the plant system.
- Assimilate portioning rate in DI plants (during start of ripening) from vegetative part to grain is higher compared to well-irrigated plants, thus increased harvest ratio (grain weight to straw weight).
- Negative impact on crop growth such as infestation of pests, diseases, anaerobic conditions in the root zone, etc. are reduced, and hence produces higher yield.

9.4.5.8 Deficit Irrigation and Wheat Yield Relationship

Hoque and Jensen (1991) found that in wheat, even during the most critical period of growth (booting to milk ripe), practicing mild water stress upto −5 bar, the grain yield reduction was not significant in comparison to the yield under the condition maintaining optimal (F.C.) water supply through the critical period. Singh (1981) observed that without prior ET deficit in the vegetative stage, wheat yields were sensitive to water deficit during critical booting/heading period but were relatively insensitive when the plants were conditioned to some 15% moisture stress in the vegetative stage. Similar response was also reported by Ali et al. (1997). Zhang et al. (2004) found that severe soil water deficit (SWD) decreased grain yield of winter wheat, while slight SWD in growth stage from spring green up to grain-filling did not evidently reduce grain yield and water use efficiency. They concluded that it is possible to reduce ET somewhat without significantly decreasing grain yield. Liang et al. (2002) demonstrated that the drying–rewatering alteration had a significant compensatory effect that could reduce transpiration and keep wheat growing, and water use efficiency significantly increased under deficit or drought condition. Maliwal et al. (2000) optimized the irrigation schedule under restricted water supply on wheat. The treatments comprised of eight levels of irrigation. All the plots received four irrigations except recommended practice, which received seven irrigations. Two irrigations, i.e., pre-sowing (immediately after dry season) and CRI stage were common. They found that four irrigations at pre-sowing, CRI, tillering, and flowering gave consistently higher yield during all the years and also in pooled. The water use efficiency was also higher. Villarreal and Kazi (1999) showed that water deficit at crown root initiation and anthesis stages had the greatest adverse effect on wheat yield. Ali et al. (2007) found that two irrigations at alternate sequence (i.e., irrigation – deficit – irrigation – deficit) in winter wheat consistently produce higher economic return under both land- and water-limiting condition.

9.4.5.9 Deficit Irrigation and Rice Yield Relationship

Alternate wetting and drying (i.e., applying irrigation after 3–5 days from disappearance of ponded water from the soil surface), a form of deficit irrigation, is regarded as water saving strategy in irrigated rice culture. About 25–40% water compared to continuous ponding water can be saved in this method, but with negligible or insignificant yield reduction.

9.4.5.10 Yield and Water Productivity Relationship Under Deficit Irrigation

Deficit irrigation can effectively boost water productivity. It is regarded as an on-farm strategy to maximize crop water productivity. But the high productivity indices in themselves are of little interest if they are not associated with high (or acceptable) yields. Such association of high productivity values with high yields has important implications for the crop management for achieving efficient use of water resources in water scarce areas. The water productivity of wheat (yield/ET) relates to the amount of irrigation water in a decreasing manner (Fig. 9.2). The irrigation water productivity (IWP, crop yield/irrigation water applied) relates to irrigation water with decreasing curvilinear relationship. At some high level of yield, incremental yield increase requires higher amounts of water to achieve. This means that IWP starts to decline as yield per unit land increases above certain levels.

9.4.6 Soil Water Potential

More direct method of scheduling irrigation requires the use of instruments that measure parameters related to moisture content. One such parameter is soil-water potential. Similar to irrigation scheduling based on soil moisture, the level of soil water potential at which crops are to be irrigated should be determined for different soil types and crop varieties.

Instruments which can measure soil water potential included tensiometers and soil moisture blocks. Tensiometers are specially well-suited for crops that are sensitive to soil moisture stress since they indicate soil moisture stress, excluding salt effects, directly in the range from field capacity, about 0.15 atmosphere to about 0.7 atmosphere. This range may represent most of the available soil moisture in sandy soils. Soil moisture blocks are generally better suited for crops that can stand a higher soil moisture stress and for soils with low salt concentrations. For high tension range, it is difficult to ascertain the tension accurately.

In a study using three moisture regimes viz. 0.25, 0.50, and 0.75 atmospheric tension measured at a depth of 22 cm, Singh and Dastane (1971) obtained optimum result irrigating at 0.25 atmosphere. Hoque and Jensen (1991) observed that even during the most critical period of growth in wheat (booting to milk ripe), for irrigation at mild water stress upto -5 bar, the grain yield reduction was not significant in comparison to the yield for irrigation in maintaining optimal water supply (at 0–0.1 bar) throughout critical period.

9.4.7 Leaf Water Potential

Leaf water potential (ψ_1) has been proposed as a measure of plant water status which can be used for scheduling irrigation (Hiller and Clark 1971; Stegman et al. 1976). Plant water deficit can be characterized directly by measuring leaf water potential, but the levels of leaf water potential limiting plant growth and yield are not generally known and must be determined for each crop or species. In addition, the effects of limiting leaf water potential at different growth stages on yield must be determined.

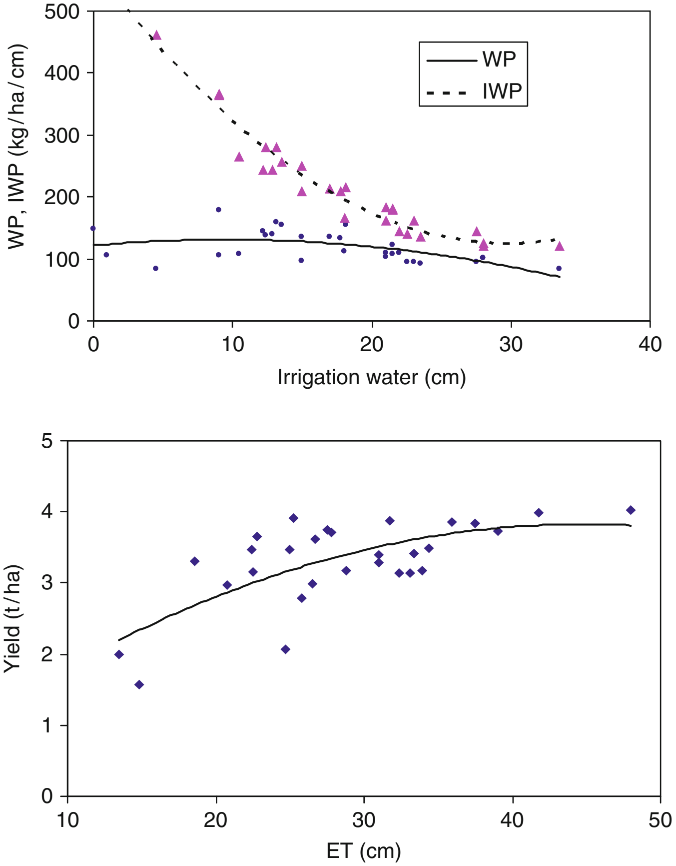

Fig. 9.2 Relationship of wheat yield and ET, and water productivity (WP), irrigation water productivity (IWP) & irrigation water (After Ali, 2008; with permission)

Usually measurements have been used based on minimum ψ_l observed near solar noon or the mean of the minimum (solar noon) and the maximum (dawn) leaf water potential.

Day time ψ_l fluctuates depending on atmospheric demand, soil water status and the degree of stomatal control of water loss (Ritchie and Hinckley 1975). In the more frequently irrigated plants, noon ψ_l decreases with the soil water with only minor fluctuations. In the drier plots, noon ψ_l is independent of the soil water status, with day to day changes occurring largely as the result varying evaporative demand with stomatal control limiting the decline in ψ_l both before or at solar noon. Thus there are a number of limitations to the use of dawn, noon, and hence mean daily values of ψ_l for irrigation scheduling in semi-arid environment. Muchow and Wood (1980) concluded on the basis of the results of their study that leaf water potential measurements made either at dawn or at noon could not be recommended as reliable guides for the scheduling of irrigation for kenaf in environments of high evaporative demand.

9.4.7.1 Shortcomings

The main limitation of this method is the instrumentation for measuring leaf water potential. Also, the levels of leaf water potential limiting plant growth and yield should be determined.

9.4.8 Stress Day Index

The stress day index (SDI) concept provides a quantitative means for determining the stress imposed on a crop during its growing season. This concept is applicable to characterization of both irrigation and drainage requirements of crops, i.e., to evaluating water and oxygen stresses.

The stress day index is determined from a stress day factor and a crop susceptibility factor. The stress day factor (SD) is a measure of the degree and duration of plant water deficit. The crop susceptibility factor (CS) indicates the plant susceptibility to a given water deficit and depends on the species and stage of development of the given crop. The stress day index (SDI) can be written as follows:

$$\mathrm{SDI} = \sum_{i=1}^{n} \mathrm{SD}_i \times \mathrm{CS}_i, \tag{9.11}$$

where n represents the number of growth periods considered.

9.4.8.1 Stress Day Factor

The stress day factor (SD) is an indication of the crop water deficiency caused by the aerial and subsurface environments. The proposed form of SD by Hiller and Clark (1971) is as follows:

$$\mathrm{SD} = E/E_{\mathrm{d}}, \tag{9.12}$$

where E is the transpiration rate, E_{d} is the atmospheric evaporative demand or potential evaporation. The values of E and E_{d} as given here would be integrated values over a specified time period, preferably but not necessarily 1 day. When no transpiration occurred, SD would be zero; SD would take on a maximum value of one when transpiration occurred at the potential rate. The value of E could be determined in many ways; possibly a soil moisture accounting procedure. The evaporative demand, E_{d}, would be best characterized by the combined method (Penman, 1948, Van Bavel, 1966; Van Bavel et. al. 1967) if necessary data were available.

9.4.8.2 Crop Susceptibility Factor

This factor is a function of the species and stage of growth of the crop. One approach to the characterization of crop susceptibility factor (CS) is to subject the crop to a specified critical SD value at different physiological growth stages (Hiller and Clark 1971; Clark and Hiller 1973). The critical SD value would be different for different species and would have to be determined in a preliminary experiment. The primary experiment for determinations of CS would be as follows:

Treatments	Yield
I Stress at growth stage I, no stress during the rest of the season	Y_{i}
II Stress at growth stage II, no stress during the rest of the season	Y_{ii}
M Stress at growth stage M, no stress during the rest of the season	Y_{m}
C No stress during season	Y_0

Then, the crop susceptibilities during each of the M growth stages would be

$$\begin{aligned}\mathrm{CS}_{\mathrm{I}} &= (Y_0 - Y_{\mathrm{i}})/Y_0\\ \mathrm{CS}_{\mathrm{II}} &= (Y_0 - Y_{\mathrm{ii}})/Y_0 \qquad (9.13)\\ \mathrm{CS}_{\mathrm{M}} &= (Y_0 - Y_{\mathrm{m}})/Y_0\end{aligned}$$

This is an experimental approach in determining CS and is best adapted to field experiments where the soil water variable can be at least partially controlled.

A second method for CS determination is to plot the crop yield (abscissa) vs. cumulative SD for a given growth period (ordinate). Then the value of CS for each period is the slope of the plot related to that period, i.e.,

$$\mathrm{CS}_i = \mathrm{SD}/\mathrm{yield}, \qquad (9.14)$$

where i is the growth period. It should be noted that by this method CS is not determined independently of SD.

Thus, there are several alternatives for calculation of SD and CS. Having chosen the suitable approach for calculating each factor, it is possible to calculate values of SDI on a daily basis, on a growth stage basis, or for the entire growing season as desired.

9.4.8.3 Advantage of SDI Method

The SDI method of irrigation scheduling has two distinct advantages over rational soil-water scheduling approaches. First, it utilizes a plant indicator of water deficit rather than a soil indicator. This is desirable because it is the plant-water deficit that affects plant yield and not soil-water deficit alone. Second, the SDI method of irrigation scheduling through the CS values accounts the fact that different plants have different sensitiveness to water deficit and that this sensitivity varies with stage of crop growth.

9.4.8.4 Shortcoming

The principal shortcoming of the SDI approach to irrigation timing is that the CS values depend on the level of water deficit (SD) permitted in their determination. To precisely utilize the SDI approach, experiments are needed for which CS values are determined not only as a function of crop species and growth stage but also as a function of level of water deficit.

9.4.9 Irrigation Calendar

Simple irrigation calendar has been suggested by the researchers to promote easy and ready adoption of improved water management practices by farmers. Irrigation calendar can be developed by:

- Using a daily soil water balance – crop yield model.
- Using long-term weather data and considering crop growth stage

In all calendar, adjustment should be maid if there is a rainfall.

The second category of technique requires estimation of reference evapotranspiration using long-term weather data and calculating crop evapotranspiration by multiplying with the particular crop-coefficient. The calculation may be done on a daily or weekly basis. Probability analysis of long-term rainfall data is performed for different levels. Generally rainfall at 75% probability level (dependable rainfall) is considered. For a particular period (say, for 7 or 10 days), the crop evapotranspiration demand minus rainfall is the water deficit. Based on the sensitivity of the crop and crop growth stage, time (interval) and amount of irrigation are scheduled (for example, at every 7 days during early stage, at every 5 days during peak growth to reproductive stage, etc.).

Irrigation calendars should be determined for each crop, normally for two or three planting dates, for the major soils, and for different initial soil water contents.

9.4.9.1 Shortcomings

Some difficulty and uncertainty (of the weather – rainfall, mean value of ET) still exist with this approach. Use of long-term average values may not be adequate during periods of hot, dry days, while over-irrigation may occur during periods of cool, cloudy days (especially if rainfall is not considered). In developing calendar, major soil groups are considered, but within a farm soil type may vary. Besides, the sowing dates mentioned in the calendar may not match with the sowing date in practice. Another difficulty may arise to maintain initial soil moisture as considered in developing the calendar. Weather condition in the past and in future may not be same. When a rainfall occurs, irrigation dates are to be adjusted, and may have the possibility of mismatching the actual situation although rules are provided for adjusting with the calendar.

9.4.10 Soil-Moisture Balance Approach or Check-Book Approach

9.4.10.1 Concept and Methodology

The check-book approach sums daily crop water use and subtracts this quantity from the available water in the effective crop root zone. When the available soil water falls below a pre-selected level, then irrigation is applied. The irrigation amount will be equal to the amount that the crop has used from the root zone storage (from the level of field capacity). If there is any rainfall, it should be added to the moisture. Prediction of irrigation date several days in advance is useful in irrigation planning and to avoid stressing the crop.

Measurement of soil moisture at the beginning of the season is necessary to obtain an initial condition estimate. Periodic review of soil moisture content during the growing season will verify water use on the water balance sheet, and allow for adjustments on the balance sheet when the estimated soil-moisture does not equal the actual soil moisture due to site specific differences.

Daily crop water use may be calculated or estimated in different ways. Pan evaporation amount can be co-related with crop water use, and then the crop water use can be calculated from pan evaporation by multiplying it with the pan coefficient. Advanced technologies such as automated monitoring of climatic conditions and soil moisture, data transmission, and computer facility make the checkbook method more practical.

9.4.10.2 Disadvantages

This method requires knowledge of effective rooting depth (as it varies with stage of development), water holding capacity of the root zone soil, daily water use, and rainfall events (if any). Periodic soil moisture measurements are also needed for checking the balance. Thus the method involves advance knowledge and technology, which is not feasible at all situations.

9.4.11 Modeling Approach for Irrigation Management

The application of systems analysis (modeling) techniques to agricultural cropping systems is now widespread. One of the most prevalent uses is in modeling crop

Table 9.2 Sample soil-moisture balance sheet for checkbook irrigation scheduling

Field ID		Crop		Emergence date
Growth stage	Days after emergence	Effective rooting depth (mm)	Water-holding capacity in root zone (mm)	Total water within root zone at present soil moisture that can be allowed to deplete at this stage (mm)
Stage 1				
....				
Stage n				

Days after emergence	Date	Total water within root zone (mm)	Crop water use (mm)	Rainfall (mm)	Irrigation applied (mm)	Resultant moisture (mm)
(1)	(2)	(3)	(4)	(5)	(6)	(7) = (3)–(4) + (5) + (6)
1						
:						

yields as influenced by various environmental parameters and amount of irrigation water application.

A number of models for scheduling irrigations under limited water supplies have been developed. Many models determine the optimal irrigation strategies using stochastic or probabilistic models of weather variables (Mapp and Ediman 1978; Rao et al. 1990). But in any season, the current weather variables can be significantly different from their probabilistic or stochastic estimates.

Now a days, FAO "CROPWATT" simulation model (Smith 1992) is used for assessing water demand and irrigation scheduling. Kuznlar (1994) applied FAO "CROPWATT" simulation model for evaluation of irrigation practice in seven different crops in central Poland. CROPWATT gave accurate results similar to actual irrigation practice in Poland. For average and wet seasons the number of actual irrigation applications agreed well with the predictions. Matching the simulated and recorded field data he noted that under irrigation had occurred in on dry season.

A numerical model "CROSOWAT" has been developed by Joshi et al. (1995) to predict the soil moisture content over the root zone depth as a function of time and to estimate the irrigation water requirement in humid basins under various management options. It has been formulated by combining six sub-models. Hanks (1974) developed a relatively simple water balance computer model for predicting dry matter and grain yields of field crops from inputs of standard soils, weather, and plant data. The model uses an empirical formula to compute the soil evaporation component (*E*) so that yield may be related to transpiration. Hanks model has been tested by Stewart et al. (1977) and Sorensen (1978). In general, the agreement between measured and predicted corn grain and dry matter yields was good. However, the model has not been extensively tested for applicability to different genotypes of corn under different water management options.

Rasmussen and Hank (1978) developed a model, a modified form of that developed by Hanks (1974) for corn, is based on water balance of irrigation, precipitation, soil water, ET, and drainage. The model has some limitations. It will not account for upward water flow if a water table exists. However, the authors claimed that this model does have the capability in that geographical area to give very reasonable yield predictions that can be utilized effectively for water stress and irrigation management application.

ORYZA2000, a model for irrigation management in rice crop, has been developed by International Rice Research Institute (IRRI). It is now used for evaluating the effect of different irrigation management options on yield and water economy, and thus selecting the best management option in relation to yield, water use, and other cultural requirements.

9.4.11.1 Limitations/Shortcomings

In modeling irrigation, the general problem is the modeling of the yield function. Furthermore, individual recommendation systems for irrigation, for fertilization and for plant protection should be integrated in one complex system. With the help of this integration one can handle better the interaction among the different individual systems.

9.4.12 Real-Time Irrigation Scheduling System

Conventional irrigation scheduling is carried out by measuring the soil moisture content of the root zone, indirect estimation of soil moisture (e.g., from tension), assessing the water content of the soil profile using water balance, or a combination. A real-time system is one in which the soil moisture monitoring task is carried out continually and automatically.

A real-time irrigation scheduling typically comprised of three main elements (Fig. 9.3), namely:

1. A soil moisture monitoring device capable of measuring soil moisture on a continuous basis.
2. The availability of a short-term weather forecast capability.
3. A decision support system which relies on field moisture status, weather forecast, and crop cultural practices to select the most appropriate course of action in scheduling irrigations.

Real-time irrigation scheduling is specially suited in drip irrigation, where the irrigation scheduling system determines the required input for the system control algorithm and hardware. An integrated real-time irrigation scheduling system has been developed by Malano et al. (1995) for the typical crop and irrigation management conditions in Southern Australia.

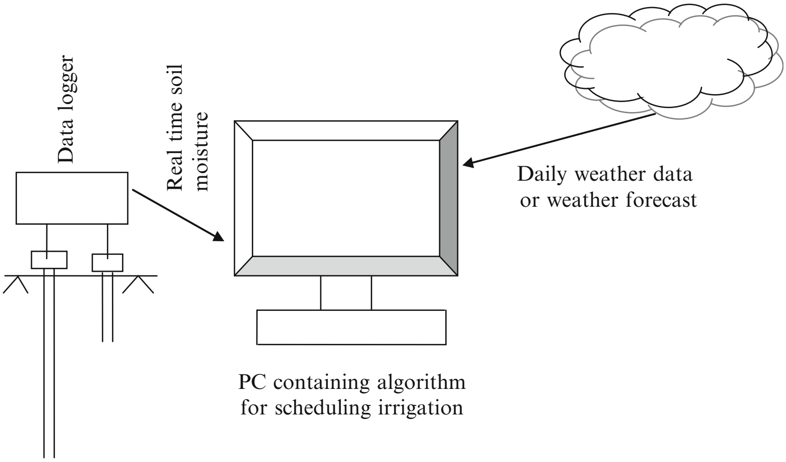

Fig. 9.3 Schematic illustration of a real-time irrigation scheduling system

9.4.12.1 Shortcoming of Real-Time Irrigation Scheduling

The main shortcoming of this approach is that, most of the available continuous soil moisture monitoring remains outside the range of afford by most of the farms/ growers. Also, integrating the system requires expertise. From the real-time system (model), the time and rhythm of irrigation is obtained. It should be ensured that no part of the field has too much or too little irrigation.

9.4.13 Irrigation Scheduling Under Limited/Variable Water Supply, Variable Rainfall, and Saline Condition

Limited and/or variable supply of water, variable rainfall, and saline conditions (soil and/or water salinity) make irrigation scheduling more challenging.

Deficit irrigation is widely used in different crops under limited water supply condition with different degrees of success. Deficit irrigation may provoke salinity if the underground water is saline. Irrigation scheduling under variable annual rainfall requires a good weather forecast to avoid either water logging or water stress, and a flexible management system to cope with rainfall uncertainty.

Scheduling irrigation under saline condition requires a different approach from the normal condition. When the salt concentration exceeds the crop tolerance limit, excess salts must be leached out from the root zone to avoid yield loss. Beyond the critical salinity level, the yield decreases almost linearly as salinity increases. Therefore in calculating irrigation depth, an additional amount of water (referred to as "*leaching requirement*") should be added for leaching, which depends on the salinity level. Technique to determine leaching requirement has been mentioned in an earlier section. In determining frequency of irrigation under saline condition, one should consider the salt concentration of soil and irrigation water, salt tolerance of the crop, long-term annual rainfall, depth to saline water-table, drainage provision, etc.

9.4.13.1 Challenges

In addition to dependent on the various inputs, the suitability and adaptability of the irrigation scheduling methods in relation to the irrigation method (surface, micro or drip, and sprinkler) is also important. New improvements in coupling irrigation methods and irrigation scheduling can provide a useful tool.

9.4.14 Sample Workout Problems on Irrigation Scheduling

Example 9.3. The soil moisture at field capacity (FC) is 25% (w/w) and the moisture content at the time of irrigating is 15% (w/w). The apparent sp. gravity is 1.25 and the depth of soil to be wetted is 40 cm. How much water in ha-cm per hectare must be applied?

Solution Given,

FC = 25% (by wt.)
Apparent sp. gravity = 1.25
Moisture at FC by vol. basis = 25 × 1.25 = 31.25%
Moisture content at irrigation time, SM_a = 15% (w/w) = 15 × 1.25 = 18.75% by vol.
Depth of soil to be wetted, d = 40 cm

$$\begin{aligned}&\text{Thus, water depth required to fill up to FC}\\&\quad = (\mathrm{FC} - \mathrm{SM_a}) \times d/100 = (31.25 - 18.75) \times 40/100\\&\quad = 5\mathrm{cm}\end{aligned}$$

Water in required depth per hectare = 1 ha × 5 cm = 5 ha-cm (Ans.)

Example 9.4. A stream of 0.0707 cumec is used to apply 32 ha-cm of water to an 8-ha field. How long will it take? What is the depth of water?

Solution
Stream size, $Q = 0.0707$ cumec
Volume of water, $V = 32$ ha-cm $= (32 \times 10{,}000)\ \mathrm{m}^2 \times (1/100)\ \mathrm{m} = 3200\ \mathrm{m}^3 = Q_t$
Time required to irrigate the field

$$\begin{aligned}t = Q_t/Q &= \left(3{,}200\,\mathrm{m}^3\right)/\left(0.0707\,\mathrm{m}^3/\mathrm{s}\right) = 45261.67\,\mathrm{s}\\&= 12.57\,\mathrm{h}(\mathrm{Ans.}).\end{aligned}$$

Size of field, $A = 8$ ha $= 8 \times 10{,}000 = 80{,}000$ m^2

Depth of water $= Q_t/A = 3{,}200$ m^3/80,000 m^2 $= 0.04$ m $= 4$ cm (Ans.).

Example 9.5. A farmer desires to irrigate a boarder which is 8-m wide and 90-m long. He wants to apply an average depth water of 8 cm to the area with a stream of 0.02 m^3/s. How long will it take to irrigate this border?

Solution
Area of boarder, $A = 90 \times 8 = 720$ m^2
Water depth, $d = 8$ cm $= 0.08$ m
Total volume of water needed, $V = A \times d = 720 \times 0.08 = 57.6$ m^3
Stream size, $q = 0.02$ m^3/s
Time required $= V/q = 57.6/0.02 = 2880$ s $= 48$ min (Ans.).

Example 9.6. The upper limit of available plant moisture (moisture holding capacity) of a loam soil is 41% (by volume) and the lower limit of plant available moisture is 19% (by vol.). The present moisture content is 36% (by vol.) and the root zone depth of the existing field crop is 40 cm. For effective use of soil moisture, irrigation is planned to apply when 75% of the plant available moisture is depleted. The average ET rate of the crop is 7 mm/day. Determine:

(a) When to irrigate ?
(b) How much to irrigate?
(c) If the application efficiency is 80% and the conveyance efficiency is 95%, determine the gross irrigation requirement.

Solution
Upper limit of plant available moisture, UPAW = 41%, v/v
Lower limit of plant available moisture, LPAW = 19% v/v
Thus, maximum plant available moisture, MPAW = 41 − 19 = 22%
Management allowed deficit, MAD = 75% of MPAW
Root depth, $d = 40$ cm
ET rate = 7 mm/day
Present moisture level = 36% v/v
Management allowed lower limit of soil moisture,

$$\begin{aligned} \text{MAL} &= \text{UPAW} - (\text{MPAW} \times \text{MAD}) \\ c &= 41 - (22 \times 75/100) \\ &= 24.5\% \end{aligned}$$

Present moisture level = 36%
Moisture in the root zone between the present and management allowed lower limit
$= (36 - 24.5) \times 40/100 = 0.046$ m $= 46$ mm

(a) Time of irrigation = moisture storage/moisture use rate

$= (46 \text{ mm})/(7 \text{ mm/day}) = 6.57 \approx 6$ days later (Ans.)

(b) Irrigation amount is the amount required to fill up to FC (upper limit of plant available moisture) from management allowed lowed limit (MAL) = [(UPAM –MAL)/100] × d

= [(41–24.5)/100] × 40 cm = 6.6 cm (Ans.)

(c) Application efficiency, $E_a = 80\% = 0.8$

Conveyance efficiency, $E_c = 95\% = 0.9$
Gross irrigation depth = net depth/($E_a \times E_c$) = 6.6/(0.8 × 0.9) = 8.7 cm (Ans.)

Example 9.7. Determine the size of the irrigation stream required to irrigate 20 ha rice field having no effective rainfall in the region and peak consumptive use rate of 9 mm/day. The irrigation system is operated for 8 h per day. The field irrigation efficiency is 80%.

Solution
Area to be irrigated = 20 ha
CU_{peak} = 9 mm/day
Field irrigation efficiency, $E_f = 80\% = 0.8$
Assume that irrigation depth per application = 10 cm
Thus, gross irrigation depth = 10/0.8 = 12.5 cm
Interval between two irrigations = net irrigation depth applied/CU_{peak} = (10 × 10) mm/(9 mm/day)
= 11.1 ≈ 11 days
Volume of water needed for one irrigation for 20 ha land, V = 20 ha × 12.5 cm
= 250 ha-cm
= (250 × 10,000) m^2 × (1/100) m
= 25,000 m^3
Daily operating period of the irrigation system = 8 h
Now, $V = q \times t$
or $q = V/t$ = 25,000/(11 × 8 × 3,600) = 0.0789 m^3/s (Ans.)

Example 9.8. An area of 50 ha (wheat field) is to be irrigated by a pump working 12 h a day. The moisture at FC and WP is 40 and 20 cm/m, respectively. The depth of root zone of the crop is 60 cm. Irrigation is to be done when 75% of the available moisture in the root zone is depleted. Peak rate of moisture use by the crop is 4 mm/day. Determine:

- Time of irrigation
- Net depth of water application
- Amount of water pumped per application
- Required capacity of the irrigation system

Assume standard value of any missing data.

Solution Given,

FC = 40 cm/m
WP = 20 cm/m

Management allowed deficit, MAD = 75% of available moisture
$ET_{peak} = 4$ mm/day
Area, A = 50 ha
Root zone depth = 60 cm
Available moisture in soil depth = FC − WP = 40 − 20 = 20 cm/m
Available moisture within the root zone = 60 cm × (20/100) = 12 cm
Available moisture within the root zone at MAD = 12 × (75/100) = 9 cm = 90 mm

(a) Date of next irrigation = (moisture storage within MAD)/ET_{peak}
= 90/4 = 22.5 days later
≈ 22 days later (Ans.)
(b) Net depth of irrigation is equal to the depletion from the root zone storage (from FC to MAD)
= 9 cm (Ans.)
(c) Amount of water required per application throughout the area,
$Q = A \times d = 50$ ha × 9 cm
= (50 × 10,000) × (9/100) = 450,000 m^3 (Ans.)
(d) Let us assume that the supply system is operated for 12 h in a day

Then, the irrigation system capacity should be such that it can deliver 450,000 m^3 water in 22 days. i.e., $Q = q \times t$
or $q = Q/t = 450{,}000\ m^3/(22 \times 12 \times 3{,}600\ s)$
$= 10.4\ m^3/s$ (Ans.)

Example 9.9. For a maize field, the following information is available:

Field capacity = 44% by volume
Wilting point = 22% by volume
Effective root zone depth = 30 cm
Average moisture content over the root zone = 35% by volume
Average daily ET rate for that period = 5 mm/day

Determine:

(a) Maximum plant available water within the root zone
(b) The time of irrigation (days from the moisture reading) allowing 75% depletion of plant available moisture
(c) Irrigation depth to be applied

Solution
(a) Maximum plant available water, PAW = (FC –WP) × R_d,
where FC is the field capacity = 44% vol., WP is the wilting point = 22% vol., and R_d is the effective root zone depth = 30 cm.
Thus, maximum PAW within the root zone = [(44 − 22)/100] × 30 = 6.6 cm = 66 mm (Ans.)
(b) Lower limit of moisture at 75% depletion of

$$\text{PAW} = 44 - (44 - 22) \times 75/100] = 44 - 16.5$$
$$= 27.5\%$$

Water depth between actual moisture and lower limit = [(35 – 27.5)/100] × 30
= 2.25 cm = 22.5 mm
Thus, time to irrigation (days from 35% moisture) = water depth/ET rate
= (22.5 mm)/(5 mm/day) = 4.5 days
≈ 4 days
That is, 4 days later (Ans.)

(c) Depth of irrigation will be equal to the depth required to fill upto FC for the root zone.
Thus, irrigation depth = [(44 − 27.5)/100] × 30 = 4.95 cm ≈ 5.0 cm = 50 mm (Ans.)

Example 9.10. Wheats (130 days duration) are grown on a silt-loam soil on Nov.15 in a semi-arid environment. Long-term monthly average of daily reference evapotranspiration (ET_0) and crop coefficient (k_c) values are given below:

	Time period (and crop growth stage)				
	Nov. (early stage)	Dec. (crop development)	Jan. (late veg./early reproductive)	Feb. (reproductive)	March (ripening)
ET_0 (mm/day)	2.0	1.8	1.9	2.8	3.0
k_c	0.7	1.2	1.3	1.4	0.8

Determine (a) total seasonal net irrigation water requirement, (b) gross irrigation requirement, and (c) irrigation schedule of the crop

Solution

(a) We know that, crop evapotranspiration, ET = ET0 × kc.
Daily average ET for the month of Nov. = $ET_0 \times k_c = 2.0 \times 0.7 = 1.4$ mm/day.
Monthly total crop water requirement (ET) for the month Nov. = daily ET × duration = 1.4 × 15 = 21 mm.
Similarly, ET for other months are calculated, and summarized in Table given below.

	Nov. (early stage) (1)	Dec. (crop development) (2)	Jan. (late veg./early reproductive) (3)	Feb. (reproductive) (4)	March (ripening) (5)
ET_0 (mm/day)	2.0	1.8	1.9	2.8	3.0
K_c	0.7	1.2	1.3	1.4	0.8
ET (mm/day)	1.4	2.16	2.47	3.92	2.4
Duration (days)	15	31	31	28	15
Monthly ET (mm)	21	66.96	76.57	109.76	36

Total seasonal ET = Σ ET = 310.29 mm

That is, net irrigation water requirement = 310.29 mm (Ans.)

(b) Considering application efficiency 95% and farm conveyance efficiency 90%, total gross irrigation requirement = 310.29/(0.95 × 0.90)
= 362.9 mm (Ans.)

(c) Number *of irrigation*
Number of irrigation during the growing season can be obtained by dividing the total irrigation requirement by irrigation depth. If we consider 40 mm irrigation depth per irrigation [considering surface (flood) irrigation], then number of irrigation = 362.9/40 = 9 nos. (Ans.)

9.5 Irrigation Command Area Designing

9.5.1 Concept of Command Area

The command area of a water supply source refers to the area which can be commanded or irrigated through the supply. Typically, it indicates the maximum area which can be covered. In a canal system, or under the area of a pump or tube-well, there are many types of land uses such as residential, roads, ponds, ditches, agricultural, barren land, etc. All the lands are not cultivable. Only the cultivable lands are considered for irrigation. But the command area involves all the area, and upto the boundary of the area.

9.5.2 Relevant Terminologies

9.5.2.1 Gross Command Area

Gross command area (GCA) is the total area within an irrigation project (canal or pump irrigation). It includes both culturable or cultivable and non- cultivable areas. That is,

$$\text{GCA} = \text{culturable command area} + \text{unculturable command area}$$

Non-culturable areas include residences, roads, schools and colleges, ponds, unfertile barren lands, problem soils, etc.

9.5.2.2 Culturable or Cultivable Command Area

It is the area which can be cultivated if irrigation facility is provided. All the cultivable lands may not under cultivation in a particular season or year due to different reasons, such as short of input, labor, etc. Cultivable command area (CCA) includes both the cultivated and culturable non-cultivated area for a particular time. That is,

$$\text{CCA} = \text{cultivated area} + \text{culturable non} - \text{cultivated area}$$

9.5.2.3 Intensity of Irrigation

All the culturable area of an irrigation project may not (and typically are not) irrigated in all seasons. A certain percentage of the area is normally irrigated. Intensity of irrigation is the ratio of area irrigated at a particular season to the culturable (or irrigable) command area and is usually expressed as percentage. That is,

$$\text{Intensity of irrigation } (\%) = (\text{area irrigated/irrigable or culturable command area in the project}) \times 100$$

9.5.2.4 Peak Irrigation Demand

It is the maximum irrigation demand rate within the growing season of crop(s). In selecting command area under a particular supply, peak irrigation demand should be considered. Otherwise, crops will suffer from water stress. Similarly, for a particular command area, channel or pump capacity should be designed based on the peak irrigation demand.

9.5.2.5 Kor Period and kor Depth

In some crops, maximum water is required at the early stage. For example in rice crop, water is needed for land preparation and as standing water. The early watering (sometimes first watering) is termed as kor watering. The portion of the base period at which kor watering is needed is termed as kor period and the depth of water required is referred to as kor depth. For example, 21 cm water is required during first 14 days in rice. Here, kor period is 14 days, the kor depth is 21 cm, and the water depth required per day is 21/14 = 1.5 cm.

9.5.3 Duty, Delta, and Base Period

9.5.3.1 Duty

The term "Duty" relates the command area coverage by the water source and the stream size. Specifically, duty refers to the irrigation capacity of the unit discharge flow. If a 2.5 cusec supply source irrigates 40 ha land, the duty of the flow is 40/2.5 = 16 ha/cusec. It is usually denoted by "D".

9.5.3.2 Delta

It is the depth of water required by a crop during its growing period for successfully grown up. It is denoted by "Δ". Delta varies with crop cultivar, weather, and cultural practices.

9.5.3.3 Base Period

It is the time period required by a crop from sowing *or* transplanting to maturity. It is denoted by "*B*". The delta increases with the increase in base period.

9.5.3.4 Relationship Among Duty, Delta, and Base Period

Let us consider an irrigation scheme, where D is the duty of the water supply source (ha/cumec), B is base period of the crop (days), and Δ is the delta of the crop (m).

By the definition of "duty," D hectares of land can be irrigated successfully (with total irrigation depth of Δ) for the "B" days with the discharge rate of one cubic meter per second (1 m^3/s).

Now, total discharge or volume of water flows from the source during "B" days at the rate of 1 m^3/s

$$\begin{aligned} &= 1\text{m}^3/\text{s} \times B\text{days} \\ &= 1\text{m}^3/\text{s} \times (B \times 24 \times 60 \times 60) \\ &= B \times 86{,}400\text{m}^3 \end{aligned} \tag{9.15}$$

On the other hand, volume of water received or accumulated in "D" hectare of land with depth (or height) Δ meter

$$\begin{aligned} &= D\text{ha} \times \Delta\text{m} \\ &= (D \times 10{,}000\,\text{m}^2) \times \Delta\text{m} \\ &= D \times \Delta \times 10^4\text{m}^3 \end{aligned} \tag{9.16}$$

Considering no other loss or gain, that is no inflow or outflow occurs in or from the system, volume of water released from the source must be equal to the volume of water received or accumulated in the sink (land). Thus equating the above two equations, we obtain the following:

$$B \times 86{,}400\,\text{m}^3 = D \times \Delta \times 10^4\text{m}^3,$$

or

$$\Delta = 8.64 \frac{B}{D},$$

i.e.,

$$D = 8.64 \frac{B}{\Delta}, \tag{9.17}$$

where D is the duty of the water supply source (ha/cumec), B is the base period of the crop (days) and Δ is the delta of the crop (m).

It is to be mentioned here that, the duty can be determined with the above relation only for single crop. For multiple crops, individual calculation is necessary.

9.5.4 Factors Affecting Peak Irrigation Demand

The command area of an irrigation scheme should be matched on the peak period irrigation demand and the supply capacity.

The factors affecting peak irrigation demand of an irrigation scheme or project are as follows:

- Irrigated area (or cultivable command area)
- Atmospheric water demand (i.e., ET rate)
- Date of sowing/transplanting of different crops
- Overlapping of different crops
- Crop types
- Sensitive stages of different crops

Sowing/transplanting of multiple crops should be designed in such a way that the peak/highest demand of all the crops does not fall at the same time

9.5.5 Identification of Problem in the Command Area

9.5.5.1 Checklist of Physical Problems

- – Check whether the land is undulating or not. Align the distribution system accordingly.
- – Check the possibility of water logging in the command area
- – Check whether the proposed crops are suitable for the soil and climate

9.5.5.2 Land Development Works

Land development works may involve the following:

- Land leveling/shaping whenever necessary
- Construction of field channels/water courses
- Drainage planning of the command area
- Construction of farm road

9.5.5.3 Financial Aspects

With the introduction of assured irrigation water, more inputs have to be applied to achieve higher yield. This may call for more finances. Banks may provide assistance to the farmers.

9.5.6 Command Area Development

The fundamentals of command area development rest on the following underlying principles:

- Selecting crops/crop rotation that require less water per day
- Minimizing wasteful losses of water
- Maximizing effectiveness of applied water
- Effective use of rainwater, if any
- Effective use of stored soil moisture

The crops to be cultivated in a season or throughout the year should be selected in such a way that peak rate water requirement does not fall at a time. The cropping pattern should be selected in such a way that the crop period (base period) distributed throughout the year, not concentrated in several months. Other points that should be taken into account are as follows:

- The channel should be aligned to reduce the length and thereby channel density.
- The main channel should be lined to reduce the seepage and percolation loss.
- The field channels should be lined to reduce conveyance loss.
- The land should be graded and proper slope should be maintained for minimizing infiltration opportunity time.
- Proper irrigation scheduling should be practiced.
- Irrigation system should be selected to minimize irrigation water requirement.
- Mode of applying water and strategy of irrigation should be selected to maximize water productivity.
- Short duration crop cultivars and less water-demanding crops should be selected (adaptable to the soil and climate) to minimize crop water requirement.

9.5.7 Designing Command Area

Design criteria for command area may categorized as follows:

- For single crop
- For multiple crops

9.5.7.1 Single Crop

For single crop, date of sowing/transplanting may be spread out within the flexible/permissible limit to minimize peak demand rate and thus to maximize irrigated command area. The maximum crop water demand may be calculated from the climatic data of the area using different tools and techniques (as described in Chap. 7, Field Water balance), and hence peak irrigation demand should then be calculated considering soil and crop characteristics. Then the command area should be designed based on the supply capacity. Design irrigable command area for a given supply of water,

$$A = D \times Q, \tag{9.18}$$

where A is the irrigable command area (ha), D is the duty of the unit discharge (ha/cumec) and Q is the minimum supply capacity (cumec).

For design purpose, minimum supply capacity (or assured/guaranteed supply capacity) should be considered to avoid any crop water stress.

In the above equation,

$$D = 8.64 \frac{B_\mathrm{p}}{\Delta_\mathrm{p}}, \tag{9.19}$$

where B_p is the length of peak period (or kor period) (days) and Δ_p is the depth of water required during the peak period (or kor period) (i.e., kor depth) (m).

Similarly, the design discharge or supply capacity for a given irrigation command can be obtained as follows:

$$Q = \frac{A}{D} \tag{9.20}$$

9.5.7.2 Multiple Crops

For multiple crops, spread sheet calculations may be needed to find out the peak water demand, and the period (i.e., time of the year) of peak demand. Then the command area for a particular supply, or the design discharge for a particular command area, can be calculated with the above formulas. The procedure has been explained with sample examples.

9.5.8 Sample Layout of a Command Area

Schematic layout of crop scheduling in a command area is shown in Fig. 9.4. The crops which need frequent irrigation (e.g., vegetables), should be close to the water source (to minimize conveyance loss), then the perennial crops, and then the short duration crops (e.g., pulses, wheat, rice).

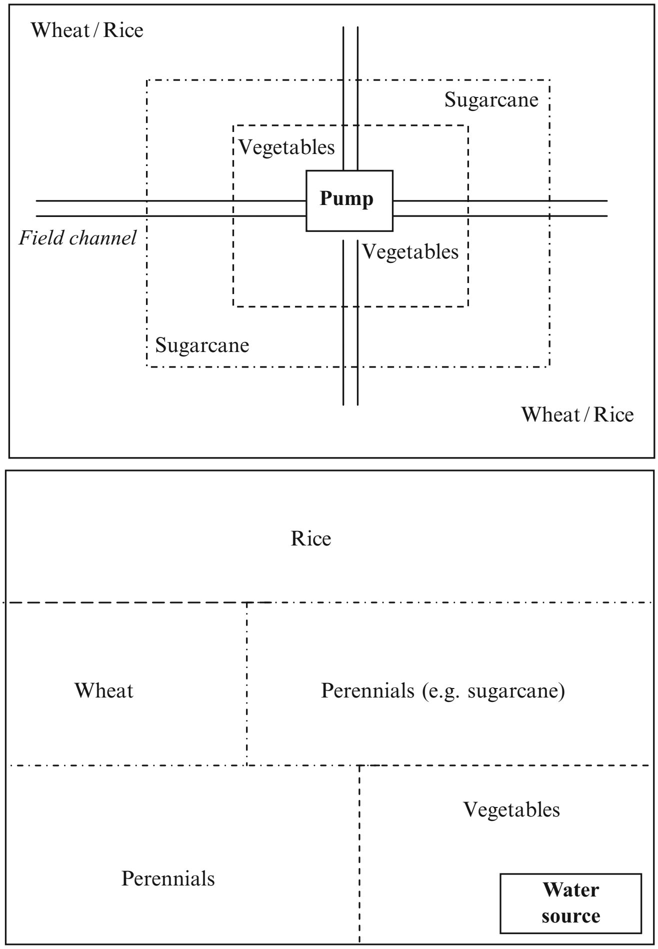

Fig. 9.4 Schematic of command area designing (crop allocation) having (a) pump at the centre, and (b) water source at a corner of the command area

9.5.9 Sample Examples on Duty-Delta and Command Area

Example 9.11. Determine the duty of an irrigation canal that runs for 140 days in a season. Only the rice crop is grown in the area (200 ha) and the delta for rice is 100 cm.

Solution
We know, duty, $D = 8.64\ B/\Delta$
Given, $B = 140$ days
$\Delta = 100$ cm $= 1$ m
Putting the values, $D = 8.64 \times 140/1 = 1{,}209.6$ ha/cumec (Ans.)

Example 9.12 A farmer used a stream of 2.5 cfs for 3 days (72 h) to irrigate 20 ha land of rice. What is the average depth of water he applied?

Solution Stream size, $Q = 2.5$ cfs $= 2.5 \times 0.0283\ \text{m}^3/\text{s}$ [1 cfs $= 0.0283\ \text{m}^3/\text{s}$]
$= 0.07075\ \text{m}^3/\text{s}$
Time, $t = 72$ h $= 259{,}200$ s
Area, $A = 20$ ha $= 20{,}000\ \text{m}^2$
We get
Total discharge during the period = water ponded in the land
i.e., $Q \times t = A \times d$
or, $d = (Q \times t)/A = (0.07075 \times 259{,}200)/20{,}000$
$= 91.69$ mm
$= 9.17$ cm (Ans.)

Example 9.13. Find out/calculate delta for wheat and rice from the following information:

Variable	Rice	Wheat
Base period	140 days	125 days
Depth of water for one irrigation	7 cm	5 cm
Interval between successive irrigations	15 days	25 days

Solution
For Rice
Base period, $B = 140$ days
Irrigation interval = 15 days
Depth of irrigation = 7 cm
No. of irrigation required = base period/irrigation interval
$= 140/15 = 9.3 \approx 9$ nos
Delta or total irrigation depth = no. of irrigation × irrigation depth
$= 9 \times 7 = 63$ cm (Ans.)
For wheat
Base period, $B = 125$ days
Irrigation interval = 25 days
Depth of irrigation = 5 cm

No. of irrigation required = base period/irrigation interval = 125/25 = 5
Delta or total irrigation depth = no. of irrigation × irrigation depth
= 5 × 5 = 25 cm (Ans.)

Example 9.14. Find out the duties of the following two irrigation systems (DTW and STW) and compare them to identify the superior irrigation one:

Variable	1st system (DTW)	2nd system (STW)
Discharge, Q	0.6 cumec	0.15 cumec
Gross command area	40 hectares	10 hectares
Intensity of irrigation	80%	90%
Base period	130 days	130 days

Solution
For DTW
$Q = 0.6$ cumec
GCA = 40 ha
Intensity of irrigation, % = 80
Area irrigated, $A = 40 \times 80/100 = 32$ ha
Duty (i.e., area irrigated per unit discharge) = $Q/A = 0.6/32 = 53.3$ ha/cumec
For STW
$Q = 0.15$ cumec
GCA = 10 ha
Intensity of irrigation, % = 90
Area irrigated, $A = 10 \times 90/100 = 9$ ha
Duty (i.e., area irrigated per unit discharge) = $Q/A = 0.15/9 = 60.0$ ha/cumec
Thus, D (STW) > D (DTW)
Hence, the second system, i.e., STW is better. (Ans.)

Example 9.15. Determine the discharge rate of the pump required to irrigate an area of 50 ha in a region having no effective rainfall and the peak ET rate of 6 mm/day. Assume the pump will be operated 12 h per day (24 h), and the field irrigation efficiency is 80%.

Solution
$A = 50$ ha = 500,000 m^2
ET rate = 6 mm/day = 0.06 m/day
Pumping operating period, $t = 12$ ha/day = 43,200 s/day
Field irrigation efficiency, $E_f = 80\%$
We can write, $Q \times t = A \times d$,
where d is the daily net irrigation depth = ET rate = 0.06 m
Thus, $Q = (A \times d)/t = 0.69$ m^3/s
Considering field irrigation efficiency, required pump discharge rate = Q/E_f = 0.69/0.80= 0.868 cumec (Ans.)

Example 9.16. A watercourse commands an irrigation area of 1,000 ha. The intensity of irrigation in a season is 80%. The peak period irrigation demand of the crop is 1.0 cm/ha per day. Determine the discharge required of the watercourse.

Solution Given,
Command area = 1,000 ha
Intensity of irrigation = 80%
Peak irrigation demand = 1.0 cm/ha-day
$Q = ?$
We get, area irrigated, $A = 1{,}000 \times 80/100 = 800$ ha
Peak period irrigation depth per day = 1 cm
Daily irrigation demand (peak period) = 800 ha × 1 cm = 80,000 m^3
Considering 12 h functional period of the canal headwork, discharge rate = $80{,}000/(12 \times 3{,}600) = 1.85\ \mathrm{m}^3$ (Ans.)

Example 9.17. In an irrigable command area of 20,000 ha, rice, wheat, maize, sugarcane, and pulses will be grown. Their monthly water requirements are shown in the table given below. The area under each crop is 30, 20, 15, 10, and 15% of the command area, respectively. Determine the required discharge capacity at the channel headwork assuming a safety factor of 1.2.

	Irrigation requirement at field (cm)				
	Rice	Wheat	Maize	Sugarcane	Pulses
Jan	20	15	16	15	
Feb	24	20	18	15	20
Mar	28	20	20	20	20
Apr	30		20	22	25
May	30			25	25
June				22	
July				23	
Aug				25	
Sep				24	
Oct				23	
Nov		15	15	18	
Dec		15	15	15	

Solution Given, irrigable command area = 20,000 ha
Area under rice = 30% = 2,000 × 30/100 = 6,000 ha
Area under wheat = 20% = 2,000 × 20/100 = 4,000 ha
Area under maize = 15% = 2,000 × 15/100 = 3,000 ha
Area under sugarcane = 10% = 2,000 × 10/100 = 2,000 ha
Area under pulses = 15% = 2,000 × 15/100 = 3,000 ha

Now
Monthly total water requirement (WR) = $\sum$(individual crop water req. × crop area)

The results are summarized below:

Month	Total monthly WR, ha-cm
Jan	246,000
Feb	348,000
Mar	408,000
Apr	359,000
May	305,000
June	44,000
July	46,000
Aug	50,000
Sep	48,000
Oct	46,000
Nov	137,000
Dec	123,000

Maximum monthly WR = 408,000 ha-cm = 40,800,000 m^3
Daily requirement = 1,360,000 m^3 (considering 30 days for 1 month)
Considering 12 h operating period of the canal headwork, and 10% conveyance loss (i.e., 90% conveyance efficiency, design discharge rate = 1,360,000/(0.9 × 12 × 3,600) = 34.98 m^3/s (Ans.)

Example 9.18. An irrigation project is proposed to command 2,500 ha of land. Rice and wheat will be grown in the area. Wheat will cover 30% of the command area and rice for the rest. Water requirement during the crop growing period (in terms of depth of water) are as follows:

	Irrigation requirement (cm)	
	Rice	wheat
Nov		11
Dec	15	10
Jan	20	10
Feb	25	12
Mar	30	13
Apr	30	

Determine the design discharge for the project.

Solution Given,

Command area = 2,500 ha
Wheat area = 2,500 × 30/100 = 750 ha
Rice = 2,500 – 750 = 1,750 ha
Now, water requirement (WR) for rice for a particular month = required water depth × rice area

The results are summarized in Table given below:

	WR, ha-m		Total WR, ha-m
	Rice	Wheat	
Nov	0	82.5	82.5
Dec	262.5	75	337.5
Jan	350	75	425
Feb	437.5	90	527.5
Mar	525	97.5	622.5
Apr	525	0	525

From the Table, it is revealed that the maximum monthly WR $= 622.5$ ha-m
Considering overall farm application efficiency of 85%, monthly peak requirement $= 622.5/0.85 = 732.4$ ha-m
Thus, daily peak demand $= 732.4/30 = 24.41$ ha-m
Considering 12 h operating period, discharge rate $= 24.41 \times 10{,}000\,/(12 \times 3{,}600) = 5.65\ \text{m}^3/\text{s}$
That is, design discharge rate $= 5.65\ \text{m}^3/\text{s}$ (Ans.)

Example 9.19. An LLP/STW discharges at the rate of 8,400 L/h and operates for 8 h each day. Estimate the area that can be commanded by the water lift if irrigation interval in each field is 15 days and the average depth of water per irrigation is 6.0 cm.

Solution Given,
$Q = 8{,}400\ \text{L/h} = 0.002333\ \text{m}^3/\text{s}$
$d = 6\ \text{cm} = 0.06\ \text{m}$
Irrigation interval = 12 days
Operating hour, $H = 8$ h/day
Let us assume that the command area = A ha
Then, $A\times d = Q \times \text{H} \times$ irrigation interval
Putting the above values, $A = [0.002333 \times (8 \times 3{,}600) \times 12]/0.06$
$= 13{,}400\ \text{m}^2 = 1.34$ ha
Hence, the command area = 1.34 ha (Ans.)

Example 9.20. The discharge of a Deep Tube-Well (DTW) is 2.5 cusec and it can be operated for 16 h daily at maximum. It is planned to cultivate rice crop in the command area. The peak consumptive use rate of the crop is estimated as 10.0 mm/day. Assuming average conveyance loss of 30%, determine the command area of the DTW.

Solution Given,

$Q = 2.5$ cusec $= 2.5 \times 0.0283 = 0.07075$ cumec [1 cusec = 0.0283 cumec]
Operating duration = 16 h/day
$\text{CU}_{\text{peak}} = 10$ mm/day $= 0.01$ m/day
Conveyance loss = 30%, and hence, conveyance efficiency (Ec) = 100–30 = 70%
Daily gross irrigation requirement, $d_{\text{gross}} = \text{CU}_{\text{peak}}/\text{Ec} = 0.01/0.7 = 0.01429$ m
Let the command area $= A\ \text{m}^2$

Considering daily demand
$Q \times t = A \times d_{\text{gross}}$
or $A = (Q \times t)/d_{\text{gross}}$
$= (0.07075 \times 16 \times 36{,}000)/0.01429\ \text{m}^2$
$= [(0.07075 \times 16 \times 36{,}000)/0.11]/100{,}000$ ha
$= 28.53$ ha (Ans.)

Relevant Journals

- Agricultural Water Management (Elsevier)
- Agricultural Systems
- Irrigation Science (Springer)
- Journal of Applied Irrigation Science (Germany)
- Irrigation and Drainage System (Elsevier)
- Trans. of the American Society of Agricultural Engineers (ASAE)
- Journal of Irrigation and Drainage Division, American Society of Civil Engineers (ASCE)
- Journal of the Institute of the Civil Engineers, London
- Journal of the Institute of Engineers (Agril. Engg. Section), Bangladesh
- Water Resources Research (American Geographical Union)
- Water Resources Bulletin (American Water Works Association)
- Hydrological Sciences Journal (Blackwell, UK)
- Field Crop Research
- Crop Science
- International Journal of BioResearch
- Agronomy Journal
- Australian Journal of Agricultural Research
- European Journal of Agronomy

FAO Papers/Reports

- FAO Irrigation and Drainage paper 24 (Crop water requirements)
- FAO Irrigation and Drainage paper 33 (Yield response to water)
- FAO Irrigation and Drainage paper 46 (CROPWAT – a computer program for irrigation planning and management)
- FAO Irrigation and Drainage paper 56 (Crop Evapotranspiration: guidelines for computing crop water requirements)
- FAO Water Report 8 (Irrigation scheduling: from theory to practice)
- FAO Water Report 22 (Deficit irrigation practices)

Questions/Exercises

1. What do you mean by crop water requirement? What are the factors influencing crop water requirement?
2. Discuss the factors influencing irrigation water requirement.
3. What are the components of total irrigation water requirement?
4. What are the indicators of irrigation need?
5. What do you mean by irrigation scheduling? Discuss the factors affecting irrigation scheduling.
6. What would be the possible strategies for irrigation scheduling?
7. Discuss the principles, merits, and demerits of different approaches of irrigation scheduling.
8. Write short note on the following:
    - Deficit irrigation
    - Irrigation calendar
    - Stress day index
    - Crop susceptibility factor
    - Real-time irrigation scheduling
9. What approach of irrigation scheduling you will suggest for your irrigation district and why?
10. For a wheat field, the following information is available:
    Field capacity = 41% by volume
    Wilting point = 19% by volume
    Effective root zone depth = 35 cm
    Irrigation is given upto field capacity considering the above root zone
    Average daily ET rate for that period = 6 mm/day
    Determine:
    (a) Maximum plant available water within the root zone
    (b) The time of irrigation (days from the moisture reading) allowing 70% depletion of plant available moisture
    (c) Depth of irrigation required
11. Wheat cultivar of 120 days duration are grown on a clay loam soil on 10 Nov. in a semi-arid environment. Long-term monthly average of daily reference evapotranspiration (ET_0) and crop coefficient (k_c) values are given below:

	Time period (and crop growth stage)				
	Nov. (early stage)	Dec. (crop development)	Jan. (late veg. to early reproductive)	Feb. (reproductive)	March (ripening)
ET_0 (mm/day)	3.0	2.1	2.0	3.0	4.0
k_c	0.75	1.25	1.3	1.35	0.7

Determine:
(a) Total seasonal net irrigation water requirement
(b) Gross irrigation requirement
(c) Irrigation schedule of the crop

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Chapter 10
Measurement of Irrigation Water

One of the major problems in surface irrigation system is the low efficiency of irrigation water. A measure that is essential for reducing waste and ensuring more efficient use among farmers is metering the volumes of water supplied and charge for it. There is a wise saying, "You cannot manage something if you can not measure it."

The amount of water that moves or passes a point in a given time period is termed as water flow rate. Measurement and determination of flow rate is a critical component of irrigation water management. Various techniques and tools are available to measure the flow rate. These range from simple indigenous methods to high-tech automated systems. Each of these methods has some advantages over the others as well as some limitations. This is the subject matter of this chapter. The techniques have been clarified with examples.

10.1 Basics of Water Measurement

10.1.1 Purpose of Water Measurement

Measurement of irrigation water is essential for making recommendations on farm irrigation practices to reduce water loss. Measuring, monitoring, and control of flow at scheme levels are important for a fair distribution of irrigation water. Other purposes of water flow measurement (irrigation pumps, stream, main or tertiary canal, etc.) are as follows:

- For hydrological water budgeting
- To document water requirement
- To charge for water used
- To develop water management plans for the effective use of water
- To document water availability baseline for evaluating any future changes and its impact on land-use and environment

M.H. Ali, *Fundamentals of Irrigation and On-farm Water Management: Volume 1*,
DOI 10.1007/978-1-4419-6335-2_10,

- To document water-use or discharge-rate for performance evaluation of water development project
- To give the irrigation provider the possibility to control the volume of water that are supplied to the scheme
- To give the Water User Associations the possibility to check the delivered flows

10.1.2 Types of Flow Measuring Devices

The methods or approaches used to measure water supplies can be broadly categorized as follows:

- Volumetric or direct measurement method
- Area-velocity method
- Tracer measurement method

In the area-velocity method, the volume of water flowing per unit time is determined with the area of flow and velocity of flow. But in the volumetric method, the discharge rate can be measured directly: the area of flow need not be determined; only the height of water over the particular section of the instrument is essential. Automated flow meters are available for different types of flow measurement, and especially for pipe flow, it is common.

Flow rate through a small opening can be measured simply by collecting the outflow for a particular time period, and then by measuring the volume of the collected water. Alternatively, a stopwatch may be used to record the time required to fill in a large container of known volume (or a particular volume). Then the flow rate,

$$Q = (\text{volume of water collected})/(\text{time required})$$

But this approach is not suitable for large discharge or open channel flow.

The tools or devices used for measuring water flow can be categorized as follows:

1. Volumetric flow measuring devices
2. Velocity measuring devices
3. Water level (height) measuring devices

The volumetric flow measuring devices are referred to as *primary devices* as water flow can be known from their measured data. On the other hand, velocity and water-height measuring devices are referred to as *secondary devices* as water flow cannot be determined directly from these readings.

10.1.2.1 Volumetric Flow Measuring Devices

This category includes weirs, flumes, V-notch, venturimeter, orifice meter, magnetic meter, ultrasonic meter, etc. Magnetic and ultrasonic meters require an electronic processor. Flumes may be of different types: Parshall flume, cut-throat flume, long-throated flume, trapezoidal flume, etc.

10.1.2.2 Velocity Measuring Devices

The instruments that fall under this category are current meter, pitot tube, float, etc.

10.1.2.3 Water Height Measuring Devices

This category includes staff gauge, meter scale, water level sensor, ultrasonic water level sensor, etc.

10.1.3 Selection of a Water Measuring Device

Various devices and tools are available for measuring discharge or flow rate. Each type of water measuring devices has advantage and disadvantage relative to the other type. Selection of a flow measuring device for a particular application or site depends on the following:

- The need of precision
- Economic factor (cost of the device)
- Easiness or limitations of the device
- Hydraulically appropriateness
- Site-specific factors
- Technical sophistication or technical know-how of the instrumentation

The type of the device that is to be selected for a particular purpose largely depends on the precision or accuracy needed for the intended use. The second factor that comes into consideration is the cost of the device, its maintenance, and operational easiness. The hydraulic factor include stream size, depth of flow, flow type such as free or submerged flow, width of the channel, characteristics of channel bed, layout and bend of the channel, turbidity of water, etc. Appropriateness of the device for the intended use is also important. The site-specific factor may include the economic condition of the farmer, social acceptance, reliance, etc. A convenient low-cost device is desirable to obtain reliable flow data.

Traditionally, cutthroat flumes have been used in open drain systems or ditches because of the ease of fabrication and installation. However, due to the extended transitional length and width associated with the cutthroat flume, transportation of the flume requires special facilitation or permits. In monitoring storm and irrigation water, plant effluent and sewage water, the Parshall flume is most widely used for permanent installation. For extremely severe industrial effluents, flume materials may be stainless steel or other special materials as needed.

The selection process often involves reaching a compromise among several features.

10.1.4 Basic Terminologies and Hydraulic Principles of Flow Measurement

10.1.4.1 Flow Rate or Discharge

The quantity of fluid flowing per second through a channel or pipe is termed as flow rate or discharge (Q). It is usually expressed in m^3/s or liter/s.

10.1.4.2 Head of the Fluid

Energy per unit weight of fluid is termed as head.

10.1.4.3 Velocity of Approach

It is the velocity with which the water approaches (i.e., reaches) the flow measuring device. Mathematically, it can be expressed as:

$$V_{\mathrm{a}} = Q/(\text{Area of flow}). \tag{10.1}$$

10.1.4.4 Continuity Equation

Continuity equation is based on the principle of conservation of mass. It states that the quantity of fluid flowing per second through a conduit at all the cross-section is constant (considering no loss from the system or gain outside the system). It can be written as:

$$Q = A_1V_1 = A_2V_2 = A_3V_3, \tag{10.2}$$

where A_1, A_2, A_3 are the area at section 1, 2, 3 and V_1, V_2, V_3 are the velocity at the sections, respectively.

10.1.4.5 Fluid Pressure: Pascal's Law

A fluid at rest (static) or in motion (dynamic) exerts pressure on its surface. In a static fluid, the intensity of pressure at a point is equal in all directions, i.e.,

$$p_{\mathrm{x}} = p_{\mathrm{y}} = p_{\mathrm{z}}. \tag{10.3}$$

10.1.4.6 Steady and Unsteady Flow

In an open channel flow, if the velocity, depth of flow, and flow rate do not change with time, the flow is termed as steady flow. On the other hand, if the velocity, depth *or* flow rate changes with time, the flow is referred to as unsteady flow.

For steady flow,

$$\frac{\mathrm{d}v}{\mathrm{d}t}=0,\ \frac{\mathrm{d}h}{\mathrm{d}t}=0,\ \frac{\mathrm{d}Q}{\mathrm{d}t}=0,\ \text{and for unsteady flow},\ \frac{\mathrm{d}v}{\mathrm{d}t}\neq 0,\ \frac{\mathrm{d}h}{\mathrm{d}t}\neq 0,\ \frac{\mathrm{d}Q}{\mathrm{d}t}\neq 0.$$

10.1.4.7 Bernoulli's Equation

Bernoulli's theorem states that, in a steady flow of an incompressible fluid, the total energy at any point of the fluid is constant.

Bernoulli's equation for nonviscous fluid between two points of a flowing path can be written as:

$$P_1+\frac{V_1^2}{2g}+Z_1=P_2+\frac{V_2^2}{2g}+Z_2, \tag{10.4}$$

where P_1 is the pressure head (i.e., pressure energy per unit of fluid) $= p/\rho g$, $V_1^2/2g$ is the kinetic head (i.e., kinetic energy per unit of fluid), V_1 is the velocity of flow, and Z_1 and Z_2 are the elevations of the two points.

The orifice, nozzle, pitot tube, and venture flow rate meters use the Bernoulli's equation to calculate the fluid flow rate using pressure difference through obstruction in the flow.

10.1.4.8 Specific Energy

Specific energy of a flowing fluid is defined as the energy per unit weight of fluid. It is given by:

$$E=h+\frac{V_1^2}{2g}. \tag{10.5}$$

10.1.4.9 Critical Depth, Critical Velocity, and Critical Flow

Critical depth (h_c) is the depth of flow when the specific energy is minimum, that is

$$h_c=\left(\frac{q^2}{g}\right)^{1/3}. \tag{10.6}$$

Velocity of flow at critical depth is known as *critical velocity*. If the velocity of flow is critical, the flow is termed as *critical flow*. Alternatively, critical flow is defined in relation to Froude number. That is, the flow is said to be critical if the Froude number (F_N) is one (1.0). Froude number,

$$F_\mathrm{N} = \frac{V}{\sqrt{gD}}, \tag{10.7}$$

where V is the mean velocity, D is the hydraulic depth of the channel (A/T), A is the wetted area, and T is the wetted perimeter.

If $F_\mathrm{N} < 1$, the flow is subcritical, and if $F_\mathrm{N} > 1$, the flow is super-critical. In other way, if the depth of flow is less than the critical depth, the depth is referred to as *subcritical depth*. Similarly, if the depth of flow is greater than the critical depth, the depth is referred to as *super-critical depth*.

10.1.4.10 Flow Through Pitot Tube

Pitot tube is a device used for measuring the velocity of flow in an open channel or pipe (Fig. 10.1). It works based on the principle of momentum of energy. If no energy loss occurs between two points in a flow path, the total energy will be the same, that is

$$\frac{p_1}{\rho g} + \frac{V_1^2}{2g} + Z_1 = \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + Z_2. \tag{10.8}$$

Here, $Z_1 = Z_2$ (two points are in the same level)
$p_1/\rho g = H$ (say) Therefore, $p_2/\rho g = H + h$

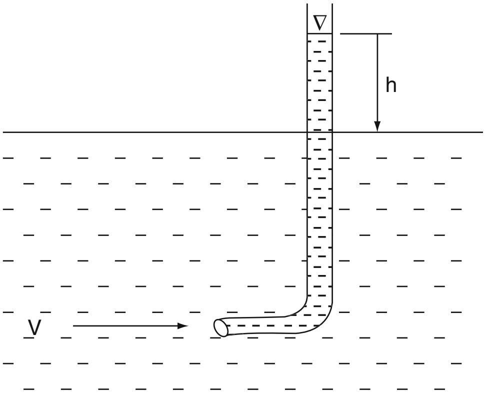


Fig 10.1 Schematic of a pitot tube

Thus,

$$H + \frac{V_1^2}{2g} = (H + h) + \frac{V_2^2}{2g}$$

Velocity head ($V^2/2g$) at point 2 is zero, as no kinetic head exists in the tube. Thus,

$$H + \frac{V_1^2}{2g} = H + h$$

or

$$h = \frac{V_1^2}{2g},$$

or

$$V_1 = \sqrt{2gh}. \tag{10.9}$$

Here, V_1 is the theoretical velocity. Actual velocity can be expressed as:

$$V_{1(\mathrm{act})} = C_\mathrm{v}\sqrt{2gh}. \tag{10.10}$$

Here, C_v is the co-efficient of velocity for the pitot tube (there is some loss of energy due to entrance in pitot tube). The $C_\mathrm{v} < 1.0$, normally 0.95–0.98.

10.1.4.11 Empirical Equation of Discharge Over Rectangular Weir

Empirical equation for discharge rate (Q) over rectangular weir (Fig. 10.2) is:

$$Q = \frac{2}{3} C_\mathrm{d} \times L \times \sqrt{2g} \times h^{3/2}, \tag{10.11}$$

where C_d is the co-efficient of discharge, L is the length of weir, and h is the head of water (or water depth).

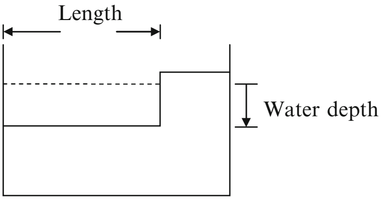


Fig. 10.2 Schematic of a weir

For a particular weir, L is constant and thus Q is dependent on h. Expressing with a single coefficient,

$$Q = Ch^{3/2}. \tag{10.12}$$

Considering velocity of approach, (10.11) can be expressed as:

$$Q = \frac{2}{3} C_{\mathrm{d}} \times L \times \sqrt{2g} \times \left[(h + h_{\mathrm{a}})^{3/2} - h^{3/2} \right], \tag{10.13}$$

where h_{a} is the velocity of approach.

10.1.4.12 Empirical Equation of Flow Over V-Notch

Empirical equation for discharge rate (Q) over V-notch (Fig. 10.3) is:

$$Q = \frac{8}{15} C_{\mathrm{d}} \times \tan\frac{\theta}{2} \times \sqrt{2g} \times h^{5/2}, \tag{10.14}$$

where, θ is the angle of notch.

For a 90° notch,

$$\tan\frac{\theta}{2} = \tan 45^{\circ} = 1.$$

Thus,

$$\begin{aligned} Q &= \frac{8}{15} C_{\mathrm{d}} \times h^{5/2} \times \sqrt{2g} \\ &= Kh^{5/2}, \end{aligned} \tag{10.15}$$

where K is the combined coefficient.

If $C_{\mathrm{d}} = 0.60$, then (10.15) reduces to:

$$Q = 1.417\ h^{5/2}.$$

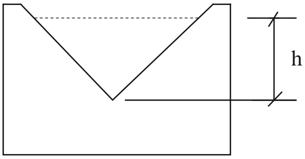


Fig. 10.3 Schematic of a V-notch

10.1.5 Permanent Flow Measuring Structure

Permanent flow measuring structures are specially designed channel shapes that characterize the flow. Common types are rectangular weirs and parshall flumes. The choice of flume or weir depends on the application – flow rate, channel shape, solid content of the flowing water, etc.

Flumes and weirs are designed to force a transition from subcritical to supercritical flow. In case of flume, the transition is caused by designing it to have a narrowing at the throat and a drop in the channel bottom. Such a transition causes flow to pass through critical depth in the flume throat. At the critical depth, energy is minimized and there is a direct relationship between water depth, velocity, and flow-rate.

10.1.5.1 Characteristics of Flow Measuring Structure

Flow measuring structures for small irrigation schemes should meet the following requirements:

- Easy and solid construction
- Low maintenance needs
- Quick and accurate readability of gauges
- Water level drop as small as possible

Long-throated flumes fit well to these requirements. The same applies to measuring weirs, but the difference in water level up- and down-stream from a weir is substantially bigger than in case of a measuring flume.

10.1.5.2 General Rules for Setting a Flow Measuring Structure

- From the hydraulic point of view, it is important to install a structure in a straight channel section with a uniform cross section, slope, and roughness. The channel must be straight upstream from the structure for a distance of 10–20 times of the water head, depending on the measuring instrument/structure.
- By using a canal drop in the design, the risk of submergence of the flow in the control section can be eliminated.

10.1.5.3 Setting Permanent Structure/Flume in the Canal

The procedure for the installation of a permanent measuring structure consists of the following phases:

- Selection of the proper location
- Evaluation of canal characteristics

- Formulation of design criteria
- Design and construction

Selection of Location

The flow measuring structure should be installed at the head of the main canals, as close as possible to the intake structure and on a well accessible site.

Canal Characteristics

The upstream water level of the structure is influenced by the shape and level of the control section of the structure, whereas the corresponding downstream water level is determined by the characteristics of the canal, namely bed width, inclination of the canal banks, longitudinal slope, and canal roughness.

Critical flow at the control section of the structure is essential. This requires a control section with an elevated and/or narrow bed than the canal in which the structure is placed. With respect to back water curve, a high and/or narrow control section causes a high upstream water level, and this may result in upstream overtopping of the embankments. On the other hand, a less high and/or less narrow control section may result in downstream water level that the flow is submerged and noncritical. So, a solution should be found in which the upstream water level is lower than the maximum level permitted, and the water level in the control section is enough for a free flow (i.e., not being influenced by a high downstream water level).

Formulation of Design Criteria

The following design criteria are to be formulated: shape of the control section, maximum and minimum flows to be measured, accuracy of the measurement, minimum freeboard, and way of measuring the upstream water level.

The maximum and minimum flows are determined on the basis of the canal capacity and on what can be expected with respect to minimum usable flow for efficient irrigation. Generally, discharge measurement errors of 5–10% are allowed for both maximum and minimum flows.

Minimum Freeboard

Freeboard requirement for the approach canal is an important element in the design of the structure. In general, a freeboard of $\sim$20% of the water level (measured from the crest invert) is recommended. In an alternate approach, the canal embankment of the relatively short approached canal should be heightened for no or lower freeboard.

Shape of the Control Section

The control section can have different shapes – triangular, rectangular, trapezoidal, round, complex, etc. From the constructional point of view, a trapezoidal-shaped control section is the preferred one, as long and wide as the canal. Such a section can be constructed by raising the bed of the canal. To irrigate a few fields upstream from the measuring flume, it is necessary to raise the upstream water level for normal and maximum flows.

Design

Nowadays, the structure is designed with the help of computer software that has been developed for each kind of structure. For example, for designing flume, software called "WinFlume" is used (Clemmens et al. 2001). The computer gives a range of design parameters (e.g., bed level raising for trapezoidal control section) with which the desired maximum and minimum flows can be measured accurately. In some cases, it may be impossible to find a solution for a given combination of criteria. In such cases, the maximum and/or the minimum flow that are to be measured with certain accuracy have to be adapted.

Normally, a metering device (e.g., meter scale) is attached with the structure at the upstream side of the transition (control section).

10.2 Measurement of Flow in Small Irrigation Channel

10.2.1 Area–Velocity Method

This method involves measurement of velocity of flow (V) and area of the flowing stream (A). Flow rate (Q) is calculated as:

$$Q = A \times V. \tag{10.16}$$

This method can be used for any size and shape of channel or conduit. It is also applicable to a wide range of flows.

In channels having irregular shape, the depth of water varies along the channel width. For that reason, multiple measurements should be made to more closely represent those changes. For discharge measurement in large stream, the entire cross-section should be divided into elementary strips of equal width (Fig. 10.4),

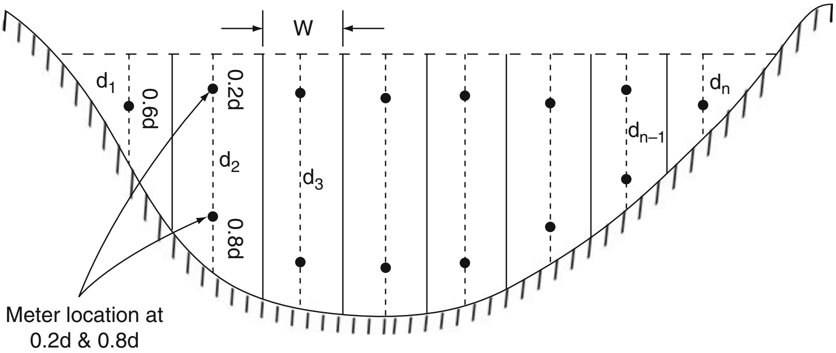


Fig. 10.4 Schematic of area–velocity method

and the current meter reading (for velocity measurement) to a depth of $0.2d$ and $0.8d$ depth (for two point method) *or* at 0.6d depth (for one point method) should be taken. The depth of water (d) at the middle of each section is determined by staff gauge or by sounding. The discharge at each strip (ΔQ) is determined as:

$$\Delta Q = \text{elementary area} \times \text{velocity} = (b \times d) \times \frac{V_{0.2d} + V_{0.8d}}{2},$$

or,

$$(b \times d) \times 0.6\ d$$

Then, total discharge,

$$Q = \sum \Delta Q = \sum_{i=1}^{n} a_i v_i, \tag{10.17}$$

where n is the number of sections in the channel.

Procedure for measurement of area and velocity are described in a later section.

10.2.1.1 Advantage

Advantages of this method include the following:

- Easy to understand
- Applicable to a wide range of stream size and flow conditions

10.2.1.2 Disadvantage

Disadvantages of this method include the following:

- Problems during very high flows
- Difficulties in measuring very slow or very small streams

10.2.2 Stream Gauging: Stage–Discharge Relationship

At a particular section of a natural large channel, with the increase in discharge, the height of water level (also termed as *stage*) and the cross-sectional area of flow increase. By surveying the shape of the channel during periods of low flow, it is possible to calculate the cross-sectional area that goes with any stage. Then, flow can be calculated at any time by observing the velocity and stage.

Thus, it is possible to develop a relationship between stage and discharge by taking measurement of velocity, stage, and calculating the discharge after different storm events. The graphical relationship between stage and discharge (discharge vs. stage) is called *flow rating curve* (Fig. 10.5). Once the relationship is developed, the discharge can be estimated from the graph with just the stage (no need of measuring the velocity), provided no permanent changes of the channel section have occurred. If there is a permanent change in the shape of the cross-section, the relationship will no longer be valid, and a new flow rating should be developed. If the new data points are drawn in previous graph, one can find a shift of the rating curve.

10.2.3 By Flume

10.2.3.1 Theoretical Aspects

For any open channel that is free flowing through a specific controlled metering structure, there is a relationship between height of inlet water and the flow rate. Whenever a given height occurs, there will always be the corresponding flow. Therefore, if we know the flow corresponding to each inlet height, we can construct a height-to-flow relationship. Then, knowing the height of water, we can find the flow rate or discharge.

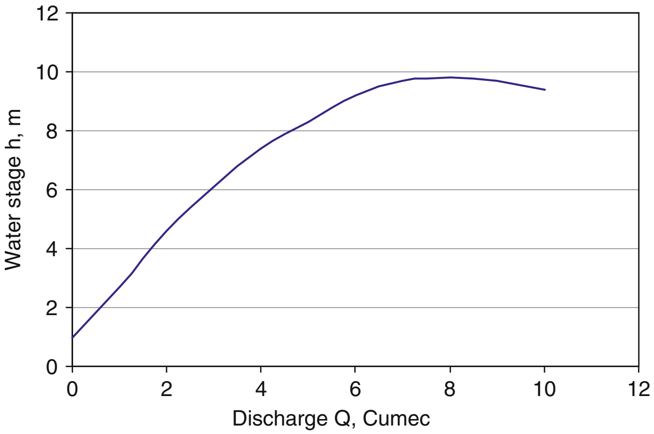


Fig. 10.5 Typical flow rating curve

Two conditions of flow can occur through a flume or weir: free flow and submerged flow. In general, submerged flow should be avoided whenever possible because it greatly complicates the calculation of the discharge rate. During free flow conditions, the discharge rate can be determined by a single depth measurement at the point of critical depth (i.e., at the throat of the flume). Submerged flow requires the measurement of both upstream and downstream depth to obtain a correction factor.

So, we have two options: install a smaller flume that will constrict the flow through the flume such that free flow conditions are created, or keep the flume and measure both the upstream and downstream depths as required for submerged flow conditions to obtain the corrected discharge.

The height of water can be determined in various ways, which will be described in a later section.

10.2.3.2 Types of Flume

Flumes are well-known hydraulic structures for measurement of discharge. They consist of a narrow section with a well-defined shape. Common types of flumes are Parshall flume, Cut-throat flume, and RBC flume. For flume inlet section, the maximum convergence ratio should not exceed 3:1. For divergence, 6:1 ratio is satisfactory.

10.2.3.3 Parshall Flume

It is also termed as critical flow venturi flume. A distinguishing characteristic of the Parshall flume is the downward sloping invert of the throat (Fig. 10.6). This feature gives it the ability to operate at higher ratios of downstream to upstream head than any other.

The working procedure for measurement of flow with flume is given below:

- Select the flume size such that the maximum operating flow is about 75–90% of flume capacity.
- A graduated scale or staff gauge should be permanently installed on a side wall of the convergence section to provide a visual height measurement of the flowing water.
- Select a channel section having straight, free from irregular sides or bottoms, slopes or other obstacles.

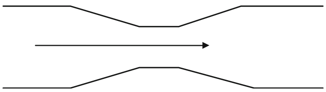


Fig. 10.6 Schematic plan view of a Parshall flume

- Set the flume in the channel with sufficient support, and check the level of the top longitudinally and transversely.

In case of measuring discharge of deep tube-well (pump), set the flume before starting of the pump.

- Observe if there is any overtopping of flow in the approach channel. Close the leakage if any.
- When the flow becomes stable and there is no bubbles or eddies, take the reading of the water depth. It is suggested to use a magnifying glass to read the fraction of the measuring unit accurately.

An ultrasonic sensor may be set above the water level on the convergence section to measure the water depth. The calibration chart of the instrument (height-discharge relation) may also be installed into the computer to get the discharge rate instantaneously, and total discharge over specified time period.

- Take several readings (at least 3) and calculate the average
- Get the discharge rate from the calibration table or by using the equation.

10.2.3.4 Cut-Throat Flume

The advantage of a cut-throat flume is economy, since fabrication is facilitated by a flat bottom and removal of the throat section (zero throat length) (Fig. 10.7a, b). Another advantage is that is that every flume has the same entrance and exit section length, which allows the same forms or patterns to be used for any desired throat width.

Cut-throat flume can operate either as a free or submerged flow structure, but requires complex correction for submerged flow. Under free flow condition, critical depth occurs in the vicinity of minimum width, which is called the flume throat or flume neck. The attainment of critical depth makes it possible to determine the flow rate knowing only the flow depth (upstream depth). The equation of flow rate for free flow condition is:

$$Q = ch^n, \tag{10.18}$$

where Q is the flow rate (m^3/s), c is the free flow coefficient, which is the value of Q when h is 1 m (which is the slope of the free flow rating when Q is plotted as a function of h on logarithmic paper), h is the upstream water depth, and n is the coefficient, which is dependent only upon the flume length.

Thus, the value of n is constant for all cut-throat flumes of the same length, regardless of the throat width.

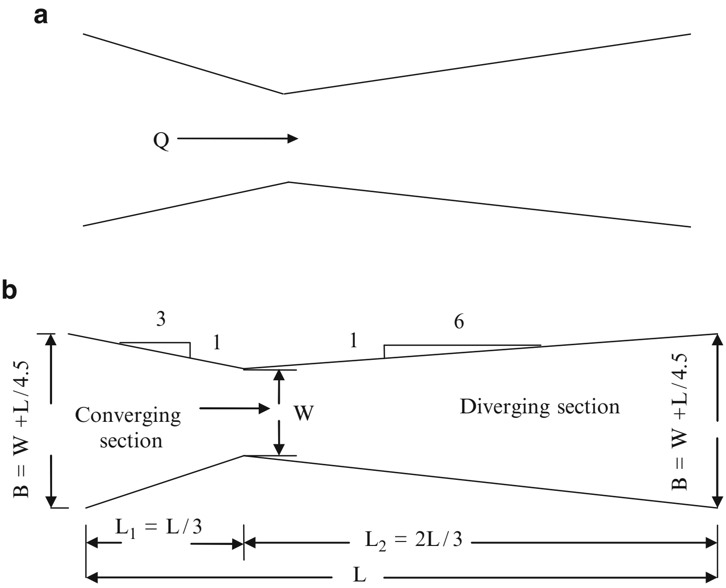


Fig. 10.7 (**a**) Schematic plan view of a cut-throat flume; (**b**) Dimension sketch of a cut-throat flume

10.2.4 By Portable Weir

A weir is a structure consisting of obstruction across the open channel having an opening (Fig. 10.8). It may be made of concrete or wood. The weir results in an increase in water level at the upstream of the structure.

The water level (or water depth or head) should be measured upstream of the weir at a distance equal to 4 to 5 times of the water head over the weir crest. Working procedure to measure discharge is almost similar to that of a flume. The water depth measurement is referenced to the horizontal crest of the weir.

Having a measurement of water depth, the discharge rate can be obtained from the calibration table or using the equation (co-efficient of the equation should be determined earlier, or have to use standard value).

10.2.5 By V-Notch

It may be referred to as a form of weir. For V-notch, only one measurement (of water depth) is required. The water depth measurement is referenced to the apex

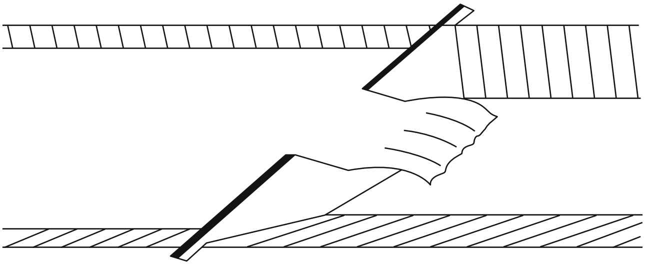


Fig. 10.8 Schematic of water flow over portable weir

(bottom point) of V-notch (as shown in Fig. 10.3). The equation for measuring discharge through a 90° V-notch is:

$$Q = Kh^{5/2}, \tag{10.19}$$

where K is the coefficient for the notch.

10.2.6 Tracer Method

10.2.6.1 Concept and Principle

In case of large flows, the measurement is a problem. Tracer or dye method is a solution for such condition. The basic procedure for tracer method involves introducing or injecting a detectable tracer or substance of known concentration in to the flow at an upstream, and measuring the concentration of the tracer at a downstream location.

10.2.6.2 Criteria of Tracer

Different tracers such as fluorescent dyes, salt, etc. can be used. Tracers should have the following criteria:

(1) The flowing water has no or a very low background value of the tracer
(2) The tracer must be readily soluble, and dissolve completely and quickly in the stream
(3) It must not degrade or react with water during the flow
(4) It should not have any toxic or hazardous effect on the aquatic system
(5) It can be detected or determined with available tools or instruments at low concentration
(6) It should be harmless to the observer

When an appropriate quantity of salt is injected into the stream, the dilution of the resulting salt shows a short pulse of elevated conductivity monitoring with a conductivity meter some distance downstream. By trial and error, the amount of salt can be determined to which the conductivity increase is measurable but not harmful to the stream organisms.

There are two methods of tracer application: (a) constant injection and (b) slug injection

10.2.6.3 Constant Injection Method

In this method, the tracer is injected at a constant rate for a period of time sufficient for the downstream to reach a steady equilibrium value. Working procedure for this method is described below:

- Prepare a concentrated solution of a tracer/soluble dye. Hot deionized water may be needed to dissolve it.
- Keep some concentrated solution for determination of concentration (say this value is C_1).
- Assemble a reliable metering pump with a good flow meter.
- Pump a constant flow of the concentrated tracer solution into the water flow.
- Allow the stream to reach steady state.
- Obtain several samples of the water downstream of the injection point.
- Analyze the water solution for concentration of the tracer (say this value is C_2).
- Analyze the original flowing water for background concentration of the particular tracer (if any). Say this value is C_0.
- Compute the unknown flow rate using the equation given below.

Let us assume
Initial background concentration of tracer in the stream = C_0
The flow rate of the stream = Q_0
Concentration of tracer in the prepared solution = C_1
Injection rate of concentrated tracer in the stream = Q_1
Concentration of tracer in the downstream water = C_2
Total downstream flow rate = $(Q_0 + Q_1)$
Applying the principle of conservation of mass,

$$(Q_0 \times C_0) + (Q_1 \times C_1) = (Q_0 \times Q_1) \times C_2$$

Thus,

$$Q_0 = \frac{Q_1(C_1 - C_2)}{C_2 - C_0}. \tag{10.20}$$

Merits

- The method is easy to understand.
- It does not require measurement of cross-section or length of channel reach.
- There is no problem if streams are highly turbulent and/or have rough irregular channels.
- It is possible in streams having large rocks and shallow flows.

Demerits

- It needs a pump to maintain a constant injection rate of tracer into the stream.
- It requires experienced personnel.
- Some tracers are toxic to the stream ecosystem.
- It needs a storage reservoir large enough to allow the tracer concentration to reach an equilibrium state in the stream.
- Excessive quantities of salt are required on large streams.
- Injection equipment and electrodes or fluorometers for detecting and measuring tracer concentration may make this method costly compared with the other method.

10.2.6.4 Slug Injection Method

This technique involves dumping a tracer of known volume and concentration into a stream and measuring the downstream concentrations over time, until the concentration of the tracer reaches the background level of the stream. The discharge is calculated as:

$$Q = \frac{(C_t - C_0)V_t}{\int_0^\infty [C_d(t) - C_0]\mathrm{d}t}, \tag{10.21}$$

where V_t is the volume of tracer solution, C_0 is the background tracer concentration, and $C_d(t)$ is the tracer concentration at the downstream section as a function of time. This equation reduces to:

$$Q = C_t V_t / (\text{area under concentration curve}). \tag{10.22}$$

The sampling interval at the downstream should be short enough to catch the peak. The tail of the curve may be fairly long.

Merit

- Does not require large reservoir for tracer

Demerit

- Sampling at downstream should be done at short intervals and for long periods, until tracer concentration becomes background level

10.2.7 Automated Instrumentation

A variety of electronic devices are used to monitor water velocity or depth at fixed location. The depth measurements are combined with channel survey data to convert depth values to flow (Fig. 10.9). Data loggers are placed on the bank and can record up to several months of observations.

The main advantage of automated instrumentation is the ability to monitor flow data continuously, especially during storms when close time intervals between measurements may be desirable. The limitations of this approach are the initial cost of the equipment, the need of a reasonable secure site for installation, expert assistance for site selection, channel survey, and installation.

10.3 Measurement of Velocity, Area, and Water Depth (or Head)

10.3.1 Measurement of Velocity

Advanced velocity measuring devices available in the market use one of the following measuring principles:

- Ultrasonic transit time
- Magnetic principle
- Differential pressure
- Float method

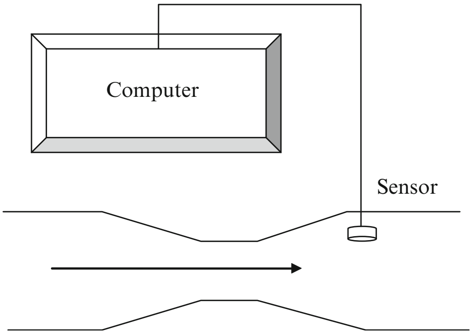


Fig. 10.9 Schematic of automated flow measuring system

Commonly used tools for measuring velocity are as follows:

- Pitot tube
- Current meter
- Surface float
- Subsurface rod
- Piezometer tube

For realizing the correct depth of velocity measurement, we should know the velocity distribution along the canal cross-section and transverse section. The schematic of velocity distribution along the canal is shown in Fig. 10.10 a, b.

10.3.1.1 Pitot Tube

A pitot tube can be used to determine the velocity of the flowing water. It works based on the differential pressure created by the flow. The velocity, V, is obtained as:

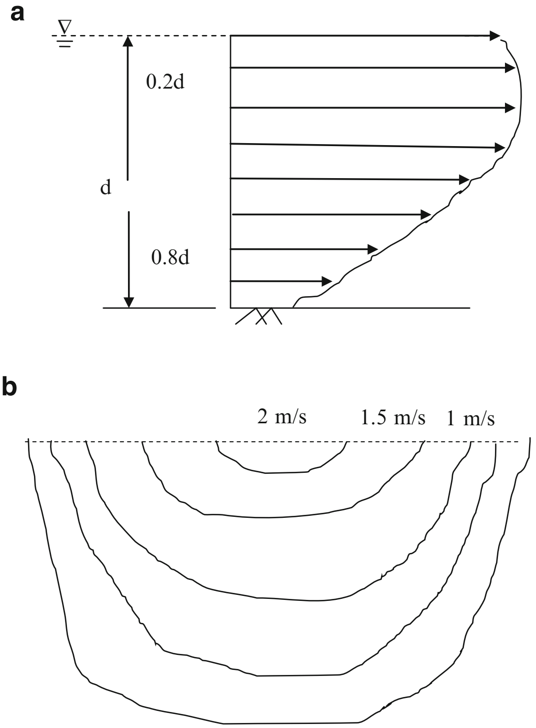


Fig. 10.10 (**a**) Schematic of vertical (transverse section) velocity distribution in canal; (**b**) Schematic of velocity distribution along cross-section

$$V = \sqrt{2gh}, \tag{10.23}$$

where h is the depth of pitot tube (centre of the inlet) from the water surface. For shallow depth of water, the pitot tube should be placed at $0.6d$ distance from the surface; where d is the depth of water in the channel. For higher depth of water, velocity should be measured at $0.2d$ and $0.8d$, and then the mean velocity should be calculated as:

$$V_{\text{mean}} = \frac{V_{0.2d} + V_{0.8d}}{2}. \tag{10.24}$$

10.3.1.2 Surface Float Method

Surface float consists of a wooden disc of 7–15 cm diameter. Time taken by floats (t) to travel a certain distance (L) is measured and surface velocity is calculated as:

$$V_{\text{s}} = L/t.$$

Then, mean velocity of flow $= 0.85\ V_{\text{s}}$.

10.3.1.3 Current Meter

Nowadays, a digital current meter is available, which when inserted in a flowing channel gives the velocity directly. As with the pitot tube, velocity should be measured at $0.6d$ depth (for shallow depth) or at $0.2d$ and $0.8d$ depths (for higher depth) and the average of the two should be taken.

10.3.1.4 Electromagnetic Gages

Electromagnetic gages are based on the principle that water moving through a magnetic field will induce a voltage that varies with the rate of water movement. These meters provide a direct reading of velocity. They are durable and benefit from having no moving parts that could get tangled in clumps of vegetation. They are costly than propeller/cup meters, and require day-to-day maintenance. They can not be used near metallic objectives or in water with very low conductivity. They are not suited in water less than 0.2 feet in depth or in very low velocities.

10.3.2 Measurement of Water Depth

Commonly used techniques for water depth measurement are as follows:

- Ultrasonic level sensor
- Submerged pressure transducer
- Meter scale
- Staff gauge

10.3.2.1 Ultrasonic Water Depth Meter (or Ultrasonic Level Transmitter)

This type of meter includes a noncontacting sensor mounted above the water level (as shown in Fig. 10.9). By measuring the transit time or time of flight from transmission of an ultrasonic pulse to receipt of an eco, the water level or head is accurately measured.

In case of flow measuring devices, measurement of water depth at the critical section is important. As the flow in the critical section is very unstable, depth of water may be measured at upstream adjacent to the structure (but with coinciding the bottom level), where the flow is subcritical and the free surface is stable.

10.3.3 Measurement of Channel Cross-Sectional Area

Channel cross-sectional area can be measured using the following approaches:

(1) Average ordinate rule
(2) Trapezoidal rule
(3) Simpson's rule

10.3.3.1 Average Ordinate Rule

In this method, the channel width is divided into a number sections or divisions (n) having equal distance (w) (Fig. 10.11). The average of the depths is calculated and area (A) is calculated as:

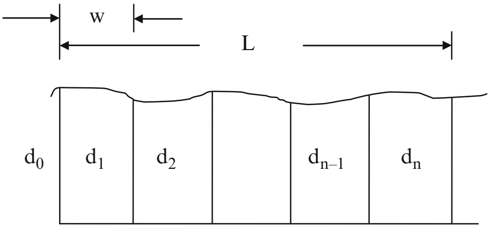


Fig. 10.11 Schematic showing of average ordinate method

$$\mathrm{A} = \frac{d_0 + d_1 + d_2 + \ldots\ldots\ldots\ldots\ldots\ldots d_n}{n+1} \times (n \times w) \tag{10.25}$$

where d_0, d_1, d_2, . . .d_n are the depths of water (from starting to ending point). This method is applicable for any number of sections (i.e., odd or even).

10.3.3.2 Trapezoidal Rule

In this method, the area is divided into a number of sections (n). Each section is considered as a trapezoid, and area is calculated as the product of average depth of the section and the section width (w). Area of a section,

$$\Delta A = \frac{d_1 + d_2}{2} \times w$$

The formula for total area (A) is:

$$A = \frac{d_0 + 2d_1 + 2d_2 + \ldots\ldots\ldots\ldots\ldots + 2d_n + d_n}{2} \times \frac{1}{n} \times (n \times w)$$

or,

$$A = w\left(\frac{d_0 + d_n}{2} + d_1 + d_2 + \ldots\ldots\ldots + d_{n-1}\right) \tag{10.26}$$

Where w is the common distance between the section ordinates. This method is applicable for any number of sections (i.e. odd or even).

10.3.3.3 Simpson's Rule

This rule is applicable to even numbers of sections or strips (i.e., having odd number of ordinates). If there is a case where sections are odd in number, Simpson's rule can be applied upto the last odd number ordinate, and then the remaining strip area can be calculated using the trapezoidal method. This method is more accurate than the other methods. The total area is calculated as:

$$A = \frac{w}{3}[d_0 + d_n + 2(d_2 + d_4 + \ldots) + 4(d_1 + d_3 + \ldots)] \tag{10.27}$$

i.e., A = (common distance/3) {(First ordinate + last ordinate) + 2 (sum of even ordinates) + 4 (sum of odd ordinates)}

10.4 Measurement of Pipe Flow/Pump Discharge

The methods include the following:

- Direct measurement
- Co-ordinate method
- By orifice meter
- By venture meter
- By flume or V-notch

10.4.1 Direct Measurement

Discharge through a small opening or pump (e.g., hand tube well, shallow pump, etc.) can be measured in this method. The outflow is collected for a given period of time in a large container of known volume or the collected water is measured with a graduated volumetric flux. The container size should be large enough to accommodate discharge for at least 15–20 s. Otherwise, the error may be higher. The time required to fill in the container may be recorded by a stop watch. The procedure should be repeated several times (3–5) and average should be taken.

Advantages of this approach are as follows:

- Easy to understand
- Low input requirement
- Low cost
- Able to measure smaller flows

Limitations of this approach include the following:

- Not feasible in higher discharge (maximum measurable flow is about 2 liters/second)
- Not practical in high velocity flows

10.4.2 Co-ordinate Method

In this method, horizontal and vertical distance traveled by a streamline is measured, and velocity of flow is calculated from these measurements. Then the flow rate is calculated by multiplying the velocity with the flowing area. Flowing area is taken as the internal diameter of the pipe (subject to the full flow of the pipe).

Let us assume that,

x = horizontal distance traveled by the water jet (m) at time t second

y = vertical distance traveled (m) at that time

V = horizontal velocity of water jet (m/s)

By definition, horizontal distance,

$$x = V \times t \tag{10.28}$$

Vertical distance,

$$y = \frac{1}{2} g t^2 y. \tag{10.29}$$

From the earlier equation, $t = x/V$. Then,

$$y = \frac{1}{2} g \left(\frac{x}{V}\right)^2 = \frac{g x^2}{2V^2}$$

Thus,

$$V^2 = \frac{g x^2}{2y}, \quad \text{or} \quad V = \sqrt{\frac{g x^2}{2y}}. \tag{10.30}$$

By measuring a horizontal distance x, and then measuring the corresponding y value, we can obtain the velocity of flow, V. The process may be repeated several times and then the average should be taken. Then, the flow rate,

$$Q = A \times V = \pi r^2 \times V, \tag{10.31}$$

where r is the inner diameter of the discharge pipe. The inner diameter can be measured with a scale (maximum travel distance from a fixed point) or a slide calipers. Two scales are needed to get the x and y value simultaneously (Fig. 10.12).

Advantage

- No sophisticated instruments are needed.

Disadvantage

- If the flow is not uniform (or vibrating one), it is difficult to obtain y value.

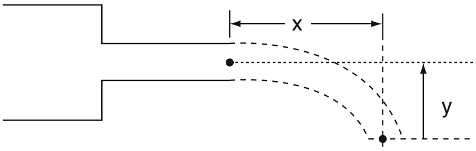


Fig. 10.12 Schematic of measurement by co-ordinate method

10.4.3 By Orifice meter

10.4.3.1 Theory

The law of conservation of energy applied to a fluid under the condition of steady, uniform flow requires the total energy of the system to remain constant. Therefore, the sum of the potential energy, pressure energy, and kinetic energy upstream of a constriction must equal the sum of the potential energy, pressure energy, and kinetic energy downstream of the constriction; assuming that no heat has been added or lost from the system.

10.4.3.2 Working Principle

The orifice meter consists of a primary element and secondary element. The primary element includes a section of straight run pipe with a constrictive device, most commonly an orifice plate (Fig. 10.13). A constriction (orifice plate) installed in a pipe will reduce the cross-sectional area of the stream flow. To maintain steady flow of fluid throughout the flow section, the velocity of the fluid will increase through the orifice. This is an increase in kinetic energy, which must be accompanied by a decrease in another form of energy. The energy changes in the form of a loss in static pressure or differential pressure. The secondary element of the orifice senses the changes in pressure or differential pressure. This differential pressure combined with correction factors for the primary device and physical characteristics of the fluid being measured allows computation of rate of flow.

The jet, where the fluid is at the highest velocity and the lowest static pressure, is known as the *vena contracts*. The cross-sectional area and location of the vena contracts are dependent on the geometry of the orifice plate and the properties of the fluid being measured.

The differential pressure is measured through pressure taps located on each side of the orifice plate.

Assuming a horizontal flow and neglecting the minor elevation difference between the points (i.e., $Z_1 = Z_2$), the Bernoulli's equation can be modified to:

$$P_1 + \frac{1}{2}\rho V_1^2 = P_2 + \frac{1}{2}\rho V_1^2, \tag{10.32}$$

where P is the pressure, ρ is the density, and V is the velocity.

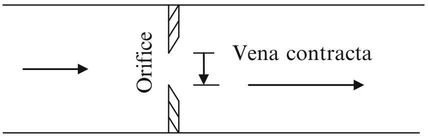


Fig. 10.13 Schematic of orifice meter

Combining with continuity equation ($q = A_1V_1 = A_2V_2$) and assuming $A_2 < A_1$, the above equation yields:

$$q = A_2\left[\frac{2\,(P_1 - P_2)}{\rho\,\{1 - (\frac{A_2}{A_1})^2\}}\right]^{1/2}.$$

For a given geometry, the flow rate can be determined by measuring the pressure difference, $P_1 - P_2$. In practice, the theoretical flow rate (q) will be smaller due to geometric conditions. Introducing a discharge coefficient (C_d),

$$q = c_d A_2\left[\frac{2(P_1 - P_2)}{\rho\{1 - (\frac{A_2}{A_1})^2\}}\right]^{1/2}.$$

Expressing P in terms of head difference between upstream and downstream (h), the above equation yields:

$$q = c_d A_2\left[\frac{2h}{1 - (\frac{A_2}{A_1})^2}\right]^{1/2}.$$

or,

$$q = c_d \times A_1 A_2 \times \frac{\sqrt{2h}}{\sqrt{{A_1}^2 - {A_2}^2}}. \qquad (10.33)$$

The discharge coefficient (C_d) is a function of the orifice opening (i.e., jet size), and the ratio of *vena contracta* to the downstream flow area. An average value of 0.60 may be considered as standard, but decreases with lower values of Reynold's number.

10.4.4 By Venturimeter

It is used to measure the rate of flow in pipe. It consists of the following parts (Fig. 10.14):

- A short converging section
- Throat
- Diverging section

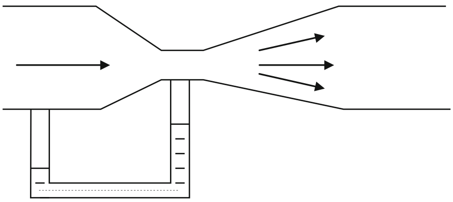


Fig. 10.14 Schematic of venturimeter and flow pattern

In the venture meter, the fluid velocity is accelerated through the converging cone of 15–20°, and the pressure difference between the upstream side of the cone and the throat is measured. The rate of flow can be calculated with the same equation of orifice meter.

10.4.5 By Flume or V-Notch

Pump discharge can be measured at the channel inlet (at the vicinity of the pump outlet) by setting flume or V-notch, with the same procedure described earlier.

10.5 Sample Workout Problems on Water Flow Rate Measurement

Example 10.1 A pitot tube having a coefficient of 0.98 is used to measure the velocity of water in a channel at 0.6*d* from the water surface. The height of water level in the tube is 30 cm. What is the velocity of flow?

Solution We know, in case of pitot tube,

$$\begin{aligned} V_{\text{act}} &= C_{\text{v}}\sqrt{2gh} = 098 \times \sqrt{2 \times 9.81 \times 0.30}\ \text{m/sec} \\ &= 2.377\ \text{m/s}\ (\textit{Ans.}) \end{aligned}$$

Example 10.2 Determine the discharge rate of water flowing over a rectangular weir of 1.0-m length when the head over the weir is 500 mm. Assume $C_{\text{d}} = 0.62$.

Solution We know, flow over rectangular weir,

$$Q = \frac{2}{3}C_{\text{d}} \times L \times \sqrt{2g} \times h^{3/2}.$$

Here, $L = 1.0$ m, $h = 0.5$ m, $C_{\text{d}} = 0.62$. Putting the values in the above equation, $Q = 0.647\ \text{m}^3/\text{s}$ (*Ans.*)

Example 10.3 The head of water in a free flowing triangular V-notch is 0.40 m. Find the discharge over it. Assume standard discharge coefficient.

Solution For a triangular V-notch, the discharge,

$$Q = \frac{8}{15} C_\mathrm{d} \times h^{5/2} \times \sqrt{2g}$$

Here, $h = 0.40$ m

$$\begin{aligned} \text{Assuming } C_\mathrm{d} = 0.60,\ Q &= \frac{8}{15} \times 0.60 \times (0.40)^{5/2} \times \sqrt{2 \times 9.81} \\ &= 0.1434\,\mathrm{m}^3/\mathrm{s}\ (Ans.) \end{aligned}$$

Example 10.4 Find the discharge over a triangular notch of angle 60° when the water head over the notch is 0.35 m. Assume $C_\mathrm{d} = 0.61$.

Solution Flow over triangular notch,

$$Q = \frac{8}{15} C_\mathrm{d} \times \tan\frac{\theta}{2} \times h^{5/2} \times \sqrt{2g}$$

$$\begin{aligned} &= \frac{8}{15} \times 0.61 \times \tan\frac{60}{2} \times (0.35)^{5/2} \times \sqrt{2 \times 9.81} \\ &= 0.06029\ \mathrm{m}^3/\mathrm{s}\ (Ans.) \end{aligned}$$

Example 10.5 The following stage and velocity data were gathered at a stream gauging station. Calculate the discharge.

Section no.	1	2	3	4	5	6	7
Velocity (m/s)	0.5	0.8, 0.6	1.2, 1.1	1.4, 1.3	1.2, 1.3	1.1, 1.0	0.8

Ordinate no.	1	2	3	4	5	6	7	8
Water depth (m)	0	1.8	2.0	2.4	2.3	2.0	1.0	0

Solution Discharge at each section,

$$\Delta Q = (b \times d) \times V,$$

where b is the uniform width of the section, d is the average depth of the section, and V is the average velocity at the middle of the section (average of $0.2d$ and $0.8d$ depth, where applicable).

Here, $b = 1.5$ m

	Section no.						
	1	2	3	4	5	6	7
Average depth (m)	0.9	1.9	2.2	2.35	2.15	1.5	0.5
Av. velocity (m/s)	0.5	0.7	1.15	1.35	1.25	1.05	0.8
ΔQ (m^3/s)	0.68	1.99	3.79	4.76	4.03	2.36	0.6

$Q = \Sigma\ \Delta Q = 18.22\ \text{m}^3/\text{s}$ (*Ans.*)

Example 10.6 In a trial to determine the discharge rate in open channel with tracer technique, the following data were collected:

Quantity of constant tracer solution injected = 500 cc/sec
Concentration of tracer solution = 0.8 gm/cc
Concentration of background tracer (originally in the stream) = 0.005 gm/cc
Concentration of tracer in the downstream sample = 0.015 gm/cc
Determine the discharge rate of the stream.

Solution We know, stream discharge,

$$Q_0 = \frac{Q_1(C_1 - C_2)}{C_2 - C_0}.$$

Here $C_0 = 0.005$ gm/cc, $Q_1 = 500$ gm/cc, $C_1 = 0.8$ gm/cc, $C_2 = 0.015$ gm/cc
Putting the values, $Q_0 = 39.25$ l/s (*Ans.*)

Example 10.7 Calculate the area from the following data by the (**a**) Average ordinate rule, (**b**) Trapezoidal rule, and (**c**) Simpson's rule

Distance in meter (m)	0	1	2	3	4	5	6
Depth (m)	0	2.0	2.5	2.6	2	1.5	0.5

Solution
(a) *By average ordinate rule*

Average depth = 1.586 m
Here, width of the section, $w = 1$ m
Number of section, $n = 6$
Total area = average depth × section width × number of section
= 1.586 m × 1 m × 6
= 9.514 m^2
Or alternatively, using the formula:

$$\begin{aligned} \mathrm{A} &= \frac{d_0 + d_1 + d_2 + \ldots\ldots\ldots\ldots\ldots\ldots\ d_n}{n+1} \times (n \times w) \\ &= [(0 + 2.0 + 2.5 + 2.6 + 2 + 1.5 + 0.5)/(6+1)] \times (6 \times 1) \\ &= 9.514\ \mathrm{m}^2\ (Ans.) \end{aligned}$$

(b) *By trapezoidal rule*

$$\begin{aligned} A &= w\left(\frac{d_0 + d_n}{2} + d_1 + d_2 + \cdots + d_{n-1}\right) \\ &= 1 \times [(0 + 0.5)/2 + 2.0 + 2.5 + 2.6 + 2 + 1.5] \\ &= 10.85\ \mathrm{m}^2\ (Ans.) \end{aligned}$$

(c) *By Simpson's rule*

Here, total number of ordinates is 6, thus number of section is odd (5). So using the Simpson's rule for the first 4 sections (5 ordinates):

$$\begin{aligned} A_1 &= \frac{w}{3}[d_0 + d_n + 2(d_2 + d_4) + 4(d_1 + d_3)] \\ &= (1/3) \times [0 + 1.5 + 2(2.5 + 2) + 4(2.0 + 2.6)] \\ &= 9.633\ \mathrm{m}^2\ (Ans.) \end{aligned}$$

Then remaining section by trapezoidal rule,
$A_2 = [(1.5 + 0.5)/2] \times 1$
$=1.0$
Total area, $A = A_1 + A_2 = 10.633\ \mathrm{m}^2$ (*Ans.*)

Example 10.8 In determining pump discharge through co-ordinate method, the following data are collected:

Inner diameter of pipe = 200 mm

Vertical distance traveled = 350 mm corresponding to a horizontal distance of 900 mm.

Calculate the discharge rate.

Solution In co-ordinate method, velocity,

$$V = \sqrt{\frac{gx^2}{2y}} = \sqrt{\frac{9.81 \times (0.9)^2}{2 \times 0.35}} = 3.369\,\mathrm{m/s}$$

Flow area, $\mathrm{A} = \pi \mathrm{r}^2 = 3.14159 \times (0.20)^2 = 0.12566\ \mathrm{m}^2$

$Q = AV = 0.42338\ \mathrm{m}^3/\mathrm{s}$ (*Ans.*)

Example 10.9 The head of water over a cut-throat flume is 300 mm having free flow. The width of maximum contraction is 600 mm. Find the discharge over the flume. Assume free flow coefficient = 0.8, flume coefficient = 0.85

Solution For free flow in cut-throat flume, discharge $Q = ch^n$

Given,
$h = 300\text{mm} = 0.3\text{m}$
$c = 0.8$
$n = 0.85$
Putting the above values, $Q = 0.2875\ \text{m}^3/\text{s}$ (*Ans.*)

Relevant Journals

- Journal of Hydraulic Engineering
- Journal of the ASCE
- Journal of the ASAE

FAO Papers

- FAO Irrigation & Drainage paper 26 (Small hydraulic structure, vol.1&2)

Questions/Exercise

1. Why is measurement of water for irrigation necessary?
2. Classify different flow measuring devices.
3. What are the factors to be considered in selecting a flow measuring device?
4. Write short notes on the following:
   - Velocity of approach
   - Steady and unsteady flow
   - Bernoulli's equation
   - Critical flow
   - Pitot tube
   - Head of the fluid
   - Pascal's law
   - Specific energy
   - Critical depth

5. Write the equation of discharge for the following: rectangular weir, V-notch, cut-throat flume
6. What is permanent flow measuring? What are the typical features of a flow measuring structure?
7. Write down the general rules for setting up a flow measuring structure.
8. Briefly describe the steps and procedures for setting up a permanent structure in the canal.
9. What is flow rating curve? Sketch a shift of flow rating curve. What are the causes of shifts in a flow rating curve?
10. Write short notes (along with the equation for flow measurement) on the following:
    (a) Area-velocity method of flow measurement
    (b) Cut-throat flume
    (c) Parshall flume
    (d) Portable weir
    (e) V-notch
    (f) Tracer method for flow measurement
11. Describe in brief the different techniques for measurement of (a) area, (b) velocity, and (c) water depth
12. Mention the different methods for pipe flow measurement.
13. A pitot tube is used to measure the velocity of water in a channel. At 0.6*d* from the water surface (where *d* is the water depth), the height of water level in the tube was found to be 38 cm.
    (a) What velocity does it indicate? Assume standard value of velocity coefficient.
    (b) If the area of flow is 1.8m^2, find out the discharge.
14. In determining flow rate in open channel with tracer technique, the following data are collected:

    Quantity of constant tracer solution injected = 400cc/s
    Concentration of tracer solution = 0.6gm/cc
    Concentration of background tracer (originally in the stream) = 0.001gm/cc
    Concentration of tracer in the downstream sample = 0.016gm/cc
    Determine the flow rate of the stream.

15. Calculate the discharge over a triangular notch of angle 80° when the water head over the notch is 0.40m. Assume standard value of coefficient of discharge.
16. In a stream gauging station, the following stage and velocity data are gathered.

Flow Section no.	1	2	3	4	5	6
Velocity (m/s)	0.6	0.7, 0.75	1.5, 1.3	1.4, 1.3	1.1, 1.2	1.0

Ordinate no.	1	2	3	4	5	6	7
Water depth (m)	0.4	1.6	2.2	2.3	2.2	1.8	0

Determine the discharge.

References

Clemmens AJ, Wahl TL, Bos MG, Replogle JA (2001) Water measurement with flumes and weirs. Publication 58, International Institute for Land Reclamation and Improvement/Alterrra - ILRI, Wegeningen, The Netherlands

Chapter 11
Water Conservation and Harvesting

The easiest and cheapest opportunities for capturing and distributing water were accessed long ago, and new schemes now cost several times more per unit of water supplied than ever before. Unless there is a sudden advance in technology (such as greatly reducing the cost of purification or desalinization, or conveyance), the cost of providing water will continue to rise. The future threats may be the nonsustainable management imposition. The solution approaches lie on the build up of engineering structures and adoption of conservation measures.

Water conservation and water harvesting, a special form of water management, are necessary in water-limited environments. They include storing and conserving activities. Artificial groundwater recharge through structures may be the most effective means for increasing groundwater potential in the rapidly declining groundwater areas. Rubber dam, a flexible structure, is a new prospect of surface water storage/harnessing. It has unique characteristics. For the successful operation, various factors should be taken into account for selecting the most suitable site for rubber dam. Various storing and conserving practices are discussed in this chapter.

11.1 Concept and Definition of Water Conservation

Water conservation is a special form of water management for water short areas, where water must be used as efficiently as possible and water losses must be minimized. A water loss is defined as the transfer of water to a place or condition from which it cannot readily be recovered for further use. Such losses include evaporation and transpiration, discharge of fresh water into salt water (oceans, lakes, or aquifers), storage or transit in the vadose (unsaturated) zone, and serious pollution by industrial, agricultural, or other chemicals. These are true losses of water. On the contrary, seepage of water from streams or irrigation canals to underlying aquifers is not always a real loss because the water can be recovered by pumping it from wells in the aquifers, or it may eventually drain into surface water. Yet, many irrigation canals are lined to "conserve" water. Thus, water

M.H. Ali, *Fundamentals of Irrigation and On-farm Water Management: Volume 1*,
DOI 10.1007/978-1-4419-6335-2_11,

conservation is best defined as the management of water to minimize the transfer of water to a place or condition that diminishes its usefulness to the intended user.

11.2 Means or Methods of Water Conservation

Water conservation can be done by adopting the following principles:

- Reducing evaporation
- Reducing transpiration/evapotranspiration
- Reducing seepage
- Reducing quality degradation
- Cloud seeding
- Increasing groundwater recharge or other storage
- Treating and reusing drainage, sewage, or other contaminated water
- Using super-absorbents

11.2.1 Reducing Evaporation

11.2.1.1 From Water Surfaces

Evaporation from lakes, reservoirs, or other water surfaces varies about 2 m/yr for dry, hot climates to 1 m/yr or less for humid, cool climates. In the 1950s and 1960s, considerable research was done to reduce evaporation from open bodies of water by covering them with monomolecular layers of hexadecanol or octodecanol. Although evaporation reductions of about 60% have been achieved under ideal conditions, actual reductions were much lower, and the use of monomolecular films to reduce evaporation from free water surfaces has found no practical application. Instead, more success has been obtained with floating objects in small reservoirs. Floating sheets of foam rubber have been successfully used. Evaporation reductions of close to 100% have been obtained with such covers.

Evaporation from open water surfaces can also be reduced by reducing the area of the water surface. For small surface storage facilities, this can be achieved by storing the water in deep, small reservoirs instead of in shallow, large reservoirs. For larger facilities, several ponds or compartmentalized ponds have to be available. When water levels in the ponds begin to drop, water is then transferred between ponds or between compartments so that only one or a few deep ponds are kept full while the others are kept dry, thus minimizing the water surface area per unit volume of water stored.

If the ponds are unlined, the effect of water depth on seepage loss from the pond must be taken into account. From a hydraulic standpoint, increasing the water depth would increase seepage the most.

11.2.1.2 From Crop Field

Evaporation from soil is reduced by dry-land farming techniques that are aimed at conserving water in the root zone during the fallow season to be used by the crop in the next growing season. The main strategies are weed control, tillage, and leaving the stubble or other crop residue in the field during the dry or fallow season. Weed control prevents transpiration losses. Tillage is primarily needed on heavy soils that may crack during fallow and lose water by evaporation through the cracks. The purpose of the tillage is then to close the cracks. Sands and other light-textured soils that do not crack are “self-mulching” and do not need tillage. Leaving the stubble or crop residue on the field during fallow periods reduces evaporation losses from the soil by lowering soil temperature and reducing wind velocities close to the soil surface.

In the Northern Great Plains of the United States, these dry-land farming techniques reduce evaporation losses by about half the annual precipitation. Thus, if the precipitation is 38 cm/yr as in eastern Colorado, dry-land farming techniques conserve about 19 cm of water per year.

11.2.1.3 Water Harvesting and Runoff Farming

In hot, dry climates, water that infiltrates the soil during small rain showers usually evaporates again during the next few days without producing significant groundwater recharge or surface runoff. Thus, another way of reducing evaporation of water from soil is to prevent infiltration of rainwater into the soil and to collect the water as runoff. This can be achieved by covering the soil with plastic, rubber, or steel sheets, or by treating the soil to reduce infiltration. These treatments can be mechanical (compaction), chemical (water repellents), physical (wax or asphalt treatments), or physico-chemical (application of sodium chloride or other dispersants to deflocculate the clay fraction of the soil). The resulting “water harvesting” systems could consist of treated catchment areas with a storage facility for storing runoff during dry periods, or of a terraced “runoff-farming” system. If a catchment-storage type facility is used, the area of the catchment and the capacity of the storage facility should be matched so that neither is over-nor-under-designed. In runoff-farming systems, crops are grown in widely spaced strips or rows treated to enhance runoff from rainfall. Thus, runoff-farming systems concentrate rainwater on the areas where crops are grown. Depending on rainfall distribution, the crops in runoff farming systems may have to be drought tolerant or at least be able to survive during periods without rain. In some cases, supplemental irrigations may be required. In addition to livestock watering and irrigation, water from water harvesting systems could be used for groundwater recharge.

Finally, evaporation of water from soil surfaces can be reduced by reducing the extent of wet areas from which water evaporates. In irrigated fields with incomplete crop covers (row crops in the beginning of the growing season, vineyards, orchards), evaporation from soil can be reduced by irrigating only the areas near the plants and leaving the rest of the soil (surface or subsurface). This can be accomplished, for example, with drip irrigation systems (surface or subsurface).

11.2.2 Reducing Evapotranspiration

This can be achieved through the following measures:

11.2.2.1 Improving Irrigation Efficiency

If crop irrigation is practiced in areas with dry climates, much of the water used in those areas would be for agriculture. Considering world average, about 75% of the total water use is for crop irrigation. Most of the irrigation systems are surface or gravity systems, which typically have efficiencies of 60–70%. This means that 60–70% of the water applied to the field is used for evapotranspiration by the crop, while 30–40% is "lost" from conveyance system, by surface runoff from the lower end of the field, and by deep percolation of water that moves downward through the root zone.

Increased irrigation efficiencies allow farmers to irrigate fields with less water, which is an economical benefit. In addition, increased irrigation efficiencies generally mean better water management practices, which, in turn, often give higher crop yields. Thus, increasing field irrigation efficiencies also saves water by increasing the crop production, thus allowing more crops to be produced with less water.

Field irrigation efficiencies of gravity systems can be increased by better management of surface irrigation systems (changing rate and/or duration of water application), modifying surface irrigation systems (changing the length or slope of the field, including using zero slope or level basins), or by converting to sprinkler or drip irrigation systems where infiltration rates and water distribution patterns are controlled by the irrigation system and not by the soil. Surface irrigation systems often can be designed and managed to obtain irrigation efficiencies of 80–90%. Thus, it is not always necessary to use sprinkler or drip irrigation systems when high irrigation efficiencies are desired.

11.2.2.2 Irrigation Scheduling

As with increased field irrigation efficiencies, improved scheduling of irrigation conserves water only if runoff and/or deep percolation from the irrigated fields cannot be reused. Scheduling of irrigation can be done based on soil water measurements (tensions and/or contents), or on estimates of daily evapotranspiration rates, using climatological methods, evaporation pans, or lysimeter. Measurement of the plant water status through remotely sensed plant or crop canopy temperatures with infrared thermometers shows promise as a technique for scheduling irrigations. Better timing of irrigation could also increase crop yields per unit of evapotranspiration (e.g., through less leaching of fertilizer), thus increasing crop water use efficiencies.

11.2.2.3 Alternate Furrow Irrigation

Different experimental results suggest that water use can be minimized (and hence the water is conserved) by almost 33% by irrigating alternate furrows instead of every furrow. In this case, most of the water savings, however, occur on the lower part of the field.

11.2.2.4 Changing Crops

Another method for reducing evapotranspiration in irrigated areas is to alter cropping patterns. In climates with hot summers and mild winters, summer crops can be minimized and more winter crops (vegetables, flowers) can be grown. In addition, crops with lower water requirements can be introduced. Where there is some rainfall, dry-land farming systems with supplemental irrigation (if necessary) can replace conventional irrigated agriculture.

11.2.2.5 Antitranspirants

Spraying plants with antitranspirants may have some application for ornamental plants (lawns and shrubs) where production or fast growth is not important. For agricultural crops, however, a reduction in transpiration usually also means a reduction in yield. Thus, antitranspirants generally are not feasible for reducing water use of agricultural crops.

11.2.2.6 Natural Vegetation and Phreatophytes

Considerable amounts of water are used by natural vegetation. To reduce evapotranspiration of natural vegetation, deep-rooted plants (trees) can be replaced by shallow-rooted plants (grasses). This often causes groundwater levels to rise and springs and streams to carry more water.

Along streams, there often is riparian vegetation that removes water almost directly from the stream. Farther away, in the flood plain, phreatophytes can grow. These are trees and deep-rooted shrubs that remove water from the groundwater. This removal causes a drop in groundwater levels, which increases stream seepage and reduces stream flow.

Water use by phreatophytes can be reduced by removing them from the flood plain (eradication). However, this is environmentally and aesthetically often undesirable. Another approach may be to lower groundwater levels in the flood plain by, for example, pumping water from wells and using it elsewhere. Groundwater levels could then be lowered to a point where some of the smaller trees and shrubs would die, but where the larger trees would be able to survive and use less water. A third approach would be channelization of the streams, using concrete or other liners to reduce or eliminate seepage altogether. In general, it is better to keep the water away from the phreatophytes than to keep the phreatophytes away from the water.

11.2.3 Seepage Control

As irrigation is the largest water use sector, it is of great important to reduce wastage. Unlined irrigation canals not only loss water, but also creates salinity problems to the adjacent land. Lining channels with concrete has the added advantage of providing better weed control and canal maintenance. The following measures may be undertaken:

(a) Lining of earth channels with concrete
(b) Replacing of channels by pipelines
(c) Applying high efficiency irrigation systems such as drip, sprinkler, and spray
(d) Application of water meters to measure the water used and charging of water rates in the case of government projects, so that the farmer would become careful in wasting water.

11.2.4 Reducing Quality Degradation

Degradation of quality to the point where water can no longer be used for its intended purpose or is no longer suitable for beneficial use, in general, is another form of water loss. Such losses occur when fresh water is polluted or when fresh water is discharged into salt water or seeps down to saline aquifers from where it no longer can be separately recovered. Where water is scarce and water conservation is a necessity, such losses should be minimized. Another example of quality degradation is urban use of water, which converts fresh water to sewage effluents.

11.2.5 Cloud Seeding

Cloud seeding is a technique for conserving water because clouds moving over an area without producing rain are a form of water loss for that area. Much work has been done over the years about the efficacy of cloud seeding. The picture emerging from these studies is that cloud-seeding should be done during rainy periods to increase precipitation so that it can be stored for future use. If cloud seeding is delayed until there is drought, there usually are not enough seedable clouds to produce significant increases in rain. Orographic storms are much more productive for seeding than convective storms. In the western United States, seeding of orographic storms is expected to increase precipitation from those storms by 10–15% (the percentage increase is higher in dry years than in wet years). The preferred seeding technique is with ground generated silver iodide crystals. Seeding from airplanes is much more expensive. Since only about 5% of the water in orographic storm clouds falls on the ground as natural precipitation, a 10–15% increase in precipitation due to cloud seeding would still leave plenty of water in the clouds for areas downwind from the seeded areas. Depending on local conditions, the economic aspects of cloud seeding can be quiet favorable.

11.2.6 Surface Storage and Groundwater Recharge

Water from cloud seeding operations or other surplus water that may be available should be stored for later use when water is scarce. Any fresh water that runs into an ocean or other place from where it cannot be recovered is a serious loss where conservation of water is important, ecological considerations notwithstanding. Water can be stored above ground behind dams or underground in aquifers. Underground storage can be enhanced by increasing the wetted area (width) of streams, using weirs or dams, or constructing levees in the streambed or flood plain. Also, groundwater recharge can be enhanced by constructing off-channel infiltration basins. Often, some form of upstream surface storage is needed to store short-term floods or other peak runoffs in the stream system. This water is then released at a slower rate from the reservoirs to allow infiltration through the downstream recharge system, so that eventually all the water is stored underground for future use. Again the best time for artificial recharge of groundwater is during wet years when there is a water surplus.

11.2.7 Treating and Reusing Sewage or Other Contaminated Water

Water reuse after treatment is not new concept. On-farm recycling of irrigation water is becoming more common. Treated effluent can also be used for recharging groundwater aquifers, and for maintenance of stream flows and wetland conditions.

11.2.8 Using Super-Absorbents

Super-absorbents are compounds that absorb and hold water in a form readily available to plants, slowly releasing this moisture in response to the change in water concentration in the surrounding medium. Their main function is to reduce moisture stress and transplant shock, thus creating optimum moisture conditions for plant growth.

Super-absorbents have the ability to make more efficient use of water, by extending the period in which soil moisture is available to plants, and by trapping gravitational water, which would normally be lost to plants in free draining soil. The water-holding capacity of the various super-absorbents available ranges from 30 to 1,000 times their own weight.

Super-absorbent compounds are available in two basic forms (Gallacher 1984):

(a) Biodegradable powders or flakes with an in-ground life span of 6–18 months. These are a combination of natural cereal-starch polymers grafted to synthetic starch polymers. Some will break down after exposure to ultraviolet rays.
(b) Nondegradable cross-linked acrylamide copolymers with a potentially indefinite life span.

11.2.8.1 Factors Affecting Absorbency

The absorption capacity of super-absorbents is affected by soil pH, salinity, and other variables that inhibit expansion of the gel particles, including some elements or ions in the growing environment. Iron and, to a lesser extent, calcium and magnesium appear to have a considerable effect in reducing absorbency when present in high concentrations, particularly with biodegradable polymers. This appears to be the only major drawback to the use of these materials.

11.2.8.2 Applications of Super-Absorbents

Super-absorbents can be used in the following four basic ways:

1. Adding to growing media in the dry form
2. Broadcasting over surfaces prior to planting or seeding
3. As a gel dip when combined with water
4. As a seed coating

In landscape construction, super-absorbents can be used as establishment aids for trees, shrubs, lawns, and instant application. Trees and shrubs are probably best treated with biodegradable absorbents, as these will assist in the first year of the plant's life and the effects will gradually diminish, enabling the plant to fully adapt to its new environment. The long-life polymers are ideally suited to use in lawn and instant turf establishment, where shallow-rooted grasses will obtain maximum benefit. Nurseries can benefit by incorporating super-absorbents into soil mixes, to reduce watering of plant stock and enable plants to retain water for longer periods when being transported.

In water-short areas, there is usually no single solution for solving problems of inadequate water supplies. Rather, a broad approach is needed, saving water, using water more efficiently, and reusing water wherever possible. Only then can limited water supplies in arid and semiarid regions be effectively managed.

11.3 Water Harvesting

11.3.1 Definition

Water harvesting is defined as the collection of rainfall or rainfall runoff (local surface runoff) for agricultural production (fruits and crops) or domestic purposes or livestock watering. The method includes storing and conserving activities.

11.3.2 Background/The Need of Water Harvesting

Water deficit in an area may arise from many factors such as low rainfall, uneven distribution, high losses due to evaporation and runoff, and absence of source of irrigation water. Seasonally dry tropics are spread over parts of 49 countries covering an area of over 20 million km^2 in five continents and support more than 600 million people mostly living at subsistence level on small farms and practicing rain-fed agriculture to meet their food and fodder requirements. Most of the Indian subcontinent falls under the semi-arid tropics where 74% of the arable land is rain-fed and contributes only 45% to the national food production. Improved rainwater management will determine the prospects of increasing crop production in such seasonally dry areas, but the management techniques may vary from region to region depending on the amount and distribution of rainfall, nature and properties of soil, crop grown, and socio-economic conditions.

11.3.3 Historical Overview: Old Practices of Rainwater Harvest

From the ancient times in several parts of the world, man has constructed the rainwater catchments and storage reservoirs and some have been preserved to this day. Rainwater is harvested as it runs off roof, or over natural ground, roads, yards, or specially prepared catchment areas. The historical sources show that the use of rainwater for domestic and other water supply begins some 4,000 years ago in the Mediterranean region. Roman villages and cities were planned to take advantage of rainwater for drinking water supply. In the hills near Bombay in India, the early Buddhist nonstick cells had an intricate series of gutters and cisterns cut into the rocks to provide domestic water on a year-round basis.

In many countries in Europe and Asia, rainwater harvesting was used widely for the provision of drinking water, particularly in rural areas. In some countries, it is still being practiced. However, where piped water supplies have been provided, the importance of rainwater as a source has been diminished. Moreover, on some tropical islands rainwater continues to be the source of domestic water supply.

Various forms of rainwater harvesting have been used traditionally throughout the centuries. The importance of traditional, small-scale systems has recently been recognized. The potential of water harvesting for improved crop production received great attention in the 1970s and 1980s. This was due to the widespread droughts in Africa, which left a trial of crop failures and a serious threat to human and livestock life.

11.3.4 Prerequisite of Rainwater Harvesting

The predetermined condition for rainwater harvesting in any area is that the area has sufficient rainfall in storms of considerable intensity, with intervals during which there is practically no or very little rainfall. It requires adequate provision for the interception, collection, and storage of the water. Depending on the circumstances, the catchment of the water is on the ground or building roofs.

11.3.5 The Need and Prospects of Water Harvesting: Case Study, Bangladesh

11.3.5.1 The Need of Water Harvesting

Bangladesh, the largest delta of the world from its ancient time, is famous for its water resource including surface and groundwater. On the one hand, the country has a network of hundreds of river, khal, beel, pond, and channel. Among the rivers, a very few of main rivers such as Padma, Surma-Megna, Jamuna, Dhaleswari, etc., keep alive during dry season (November to April). On the other hand, a large number of rivers dried up during dry season and a remarkable number of rivers are fully died. A few of the water bodies such as khal, beel, ponds, etc., contain water during dry season. This problem is severe in the north and north-west part of Bangladesh. Moreover, there is a common problem of falling water table during dry season. This may happen due to insufficient recharge to groundwater, reduced flow rate at rivers due to construction of barrage at upstream, unplanned installation of tube wells, excessive withdrawal of groundwater, etc. Recently, contamination of groundwater by arsenic added a new era.

Under the above circumstances, to increase agricultural production from a reduced piece of land to feed an ever-increasing population, alternative strategy or new source for extra water need to be identified for exploitation.

11.3.5.2 Prospects of Water Harvesting

The sources of water in Bangladesh are surface water, groundwater, and rainwater. About 93% of the stream flow passing through the country originates from outside Bangladesh. Rainfall within the country contributes to the total water available, a part of which infiltrates into ground to recharge existing groundwater and the remaining rainwater flows as surface run-off.

The annual rainfall of Bangladesh varies from a minimum of 1,200 mm to a maximum of 5,800 mm (having spatial and temporal variation) with an average of 2,200 mm. About 85% of the annual rainfall is received during the monsoon months (May to September) (Fig. 11.1). November to February is almost dry, but some rains are received during March and April. The rainfall distribution data indicate that there are possibilities of harvesting excess monsoon rainwater for its use during dry periods. Since higher and more stable crop yields require optimal soil moisture, water harvesting can improve the reliability of plant-available moisture, and hence improved the yield.

11.3.6 Techniques of Rain-Water Harvesting

Various techniques have been evolved for harvesting rain-water. These include from traditional or ancient technique to modern rubber dam. Selection of appropriate technique for a site depends on various factors such as source (distance) and amount of rain-water, soil condition, technical, and socio-economic condition.

11.3.6.1 Rain-Water Harvest from External Catchment

This system involves the collection of runoff from external areas, which is at an appreciable distance from where it is being used. Runoff from natural drainage is

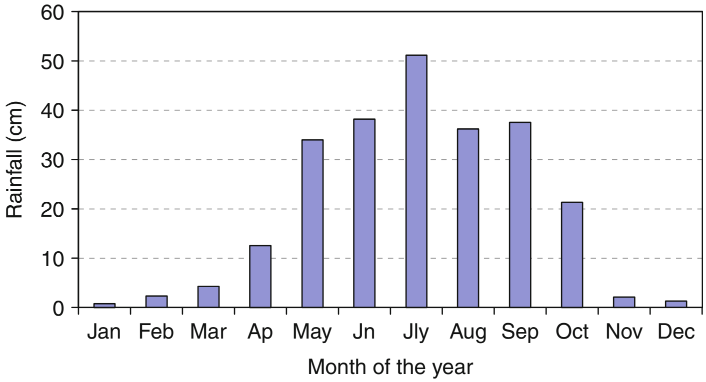


Fig. 11.1 Pattern of annual rainfall distribution in Bangladesh

diverted toward collection point through diversion ridge. The runoff water is sometime conveyed through structures of diversion and distribution networks. This is sometimes used with intermediate storage of water outside the catchment basin for later use as supplementary irrigation.

11.3.6.2 In Situ Rain-Water Harvest

This may be accomplished by deep tillage, contour farming, agronomic practices, mulching, or a combination. This approach works better where the water holding capacity of the soil is higher and organic matter is rich. The stored soil moisture may be sufficient for germination, establishment, and maturity of some dry-land crops. In in-situ rain-water harvesting, high volume of runoff can not be stored in soil profile.

Deep tillage increases water holding capacity of soil through increasing porosity and infiltration rate, and facilitates root elongation. Thus, moisture and nutrient uptake from deeper layer increases. Mulching through crop residues reduces surface runoff and evaporation loss from the soil profile. Tillage mulching of top few centimeter soil breaks the capillary channel of water movement, thus reduces moisture loss through evaporation.

11.3.6.3 Harvesting in Farm-Pond

In this approach, a suitable size pond is constructed at a corner or center of the individual farm. Water is stored in this pond during monsoon period or from heavy rainfall events. Water can be harvested through runoff collection.

Rainwater harvesting can be a valuable practice increasing crop production in semi-arid regions. It is also useful in humid and subhumid region during dry or off-monsoon period, and even in monsoon for long dry-spell. In semi-arid region, water harvested in a farm-pond can be used to irrigate low water demanding crops and irrigating only at critical growth stages (which is sensitive to water stress/ deficit). Supplemental irrigation from farm pond during dry spell can ensure sustained and higher crop yield.

11.3.6.4 Rain-Water Harvesting with Storage

In this approach, the harvested water is stored in dams or water holes. Small dams are normally constructed across the width of the natural channel in hilly areas where the channel width is narrow and the slope is not so high, and the dam can store sufficient water. Earthen, concrete, and/or rubber dam can be build depending on the availability of raw material, cost, and economic, and technical factors.

11.3.7 Sample Examples on Rainwater Harvesting

Example 1. In a dry area, rainwater is harvested in an existing farm pond for dry-season crop cultivation. The volume of water estimated in the pond is 225 m^3. A low water demanding crop is planned to cultivate requiring 10 cm water for irrigation at two water sensitive growth stages. How much area can be irrigated with the stored water?

Solution Given
Volume of water, $V = 225\ m^3$
Depth of irrigation, $d = 10 = 0.10$ m
Thus, area can be irrigated, $A = V/d = 225/0.1 = 2{,}250\ m^2$
$= (2{,}250/10{,}000) = 0.225$ ha (*Ans.*)

Example 2. A farmer has an area of 2 ha, and he planned to cultivate this land in dry season through harvesting water by digging a pond near the land. The average percolation and evaporation loss from the pond during the period of harvesting to start of irrigation (90 days) is 1.5 mm per day. Depth of water needed for irrigating the field is 6 cm. Determine the size of the pond that the farmer should be dug.

Solution Total water loss during the period $= 90 \times 1.5 = 135$ mm $= 0.135$ m
Assume that the maximum allowable depth of the pond = 3 m
And, depth of water at the end of harvesting = 2.5 m
Thus, water depth at irrigation period = water depth − loss = 2.5 − 0.135 = 2.365 m
Given, depth of irrigation req. = 6 cm = 0.06 m
Volume of water needed for the field $= A \times d$
$= (2 \times 10{,}000\ m^2) \times 0.06$ m
$= 1{,}200\ m^3$
Thus, the required area of the pond (having 2.365 m water depth at the beginning of irrigation) $= V/d_w$
$= 1{,}200\ m^3/2.365\ m = 507.4\ m^2$
Let the width of the pond = 20 m
Then, length = 507.4/20 = 25.4 m
Thus, the pond size is: 25.4 m × 20 m × 3 m (*Ans.*)

11.4 Groundwater Recharge

11.4.1 Extent and Magnitude of the Problem

Recharge is the process by which groundwater is replenished. It occurs as rain and surface water percolates down through the natural filter constituting fine-grained soil. When a balance between recharge and extraction is maintained, the groundwater aquifer remains static. But it falls down when the extraction rate becomes higher than the rate of recharge.

With the advent of the "Green Revolution" in 1960s, a significant area in many parts of the world is occupied under rice–wheat cropping sequence. Among the cereals, rice is regarded as high water consuming crop. Because of continuous withdrawal of groundwater for stabilized and ensured crop yield, water-table is declining continuously. The scenario is common in many parts of central and south Asia. Besides, in many towns and cities of the world, the water-table is declining abruptly due to over-extraction (Sarkar and Ali 2009).

11.4.2 Methods of Groundwater Recharge

To prevent further decline in groundwater that in-fact may initiate/accelerate the desertification process in many areas, priority should be given to harvest the excess water. However, the availability of excess water and favorable geo-hydrological conditions are the prerequisites for successful implementation of such a program.

Options of recharge include the following:

(a) Recharge from natural water bodies
(b) Artificial recharge

- From mass land by making ridge
- Through canal water supply during off-irrigation season
- By making dam/sluice gates
- Through recharge well
- Through land-overflow
- Recharge by making large reservoir

11.4.2.1 Recharge from Natural Water Bodies

Exposure of the soil to the water is a must in the recharging process. Water bodies have an important role in recharge. Water from the water bodies continuously seeps into the ground.

11.4.2.2 Artificial Recharge

Recharge can be augmented through artificial arrangement. Artificial groundwater recharges through structures may be the most effective means for increasing groundwater potential in the rapidly declining groundwater areas. Artificial recharge includes several ways to recharge, from low cost to high cost involvement:

- Recharge from crop lands by making ridge
- Recharge through canal water supply during off-irrigation season
- Recharge through land-overflow/infiltration basin
- Recharge by making dam/sluice gates
- Recharge by making large reservoir
- Recharge through tube-well (recharge well)

11.4.2.3 Recharge from Crop Lands by Making Ridge

During the period of heavy rainfall or monsoon, farm lands can be used as a recharge area. If the lands are bounded by high ridges (~30 cm), the water can be percolated downward, and ultimately to the groundwater/aquifer. This is an easy way and involves no additional cost. Only requirement is the initiation and motivation of the mass people.

11.4.2.4 Recharge Through Canal Water Supply During Off-Irrigation Season

In many regions of the world, rainfall runoff and limited canal water during lean periods of irrigation requirement may be utilized for artificial groundwater recharge.

11.4.2.5 Recharge Through Land-Overflow/Infiltration Basin

Water can be spread over vast land (infiltration basin) and provide opportunity to infiltrate and percolate. Sufficient bund (barrier) should be provided to hold the water within a regime.

The performance of infiltration basins for artificial recharge of groundwater is very site-specific, and some local experimentation normally is necessary before a system can be designed and operated for maximum performance. Aspects to be studied include the optimum size and depth of the basins, optimum lengths of flooding and drying periods, response of groundwater to recharge, etc. Artificial recharge of groundwater with infiltration basin requires presence and availability of land with sufficiently permeable soils (loamy sands or coarser) to give acceptable infiltration rates. Also, aquifers should be unconfined. Where these requirements are not met, artificial recharge can be achieved with recharge wells.

11.4.2.6 Recharge by Making Dam/Sluice Gates

Recharge from large land surfaces can be facilitated through stagnating water by artificial barrier. The barrier may be sluice gate, dam, or other forms depending on the catchment size, outlet, and other physiographic and hydraulic condition.

11.4.2.7 Recharge by Making Large Reservoir

Recharge can be augmented through creating recharge area. Recharge area can be established by making large reservoir in suitable low-land area, where water is compounded or provided, and thus facilitating recharge for long time.

11.4.2.8 Recharge Through Tube-Well (Recharge Well)

The recharge tube-well admits water from the surface and conveys it to fresh water aquifer. Large amount of water can be recharged through recharge well. In many regions of the worlds, although the region may have moderate or low average rainfall, high intensity rainfall creates flash flood that goes to the sea as waste. Such flash floods need to be arrested at various locations for recharge at accelerated rate. In flat topography, where extensive groundwater development has taken place at shallow depth (in the first aquifer of 20–60 m depth), recharge structures with tube well are often better choice than surface storage. In areas having alluvial aquifers with good transmissibility, hydraulic conductivity, and specific yield, recharge tube wells improve water quality and availability more quickly than gradual percolation from percolation tank or check dams.

Wells for artificial recharge are similar in construction to wells for pumping. A filter pit is to be excavated and filled with filter material. Filter materials should be designed properly, so that suspended solids and contaminants can not enter to the aquifer. The filter materials would be in the order – pebbles at the bottom, then gravels, and then coarse sand at the top (Fig. 11.2). Mechanical analysis of the base material (soil from the canal bed or surrounding soils) should be made for proper design of filter. Even then, recharge wells tend to become clogged and must be cleaned or redeveloped. For wells in alluvial materials, specific capacities for recharge often are only 25–75% of those for pumping. The cost of groundwater recharge with injection wells usually is about an order or magnitude higher than with infiltration basins. The flow pattern of the recharge well is the reverse of the pumping tube-well pattern (Fig. 11.2).

11.5 Rubber Dam: A New Prospect of Surface Water Storage/Harnessing

11.5.1 Definition and Types of Rubber Dam

Rubber dam is a new hydraulic structure when compared with steel sluice gate. It is made of high-strength fabric adhering with rubber, which forms a rubber bag anchoring on basement floor of dam. It is a flexible hydraulic structure (inflatable

Fig. 11.2 Schematic of a recharge well

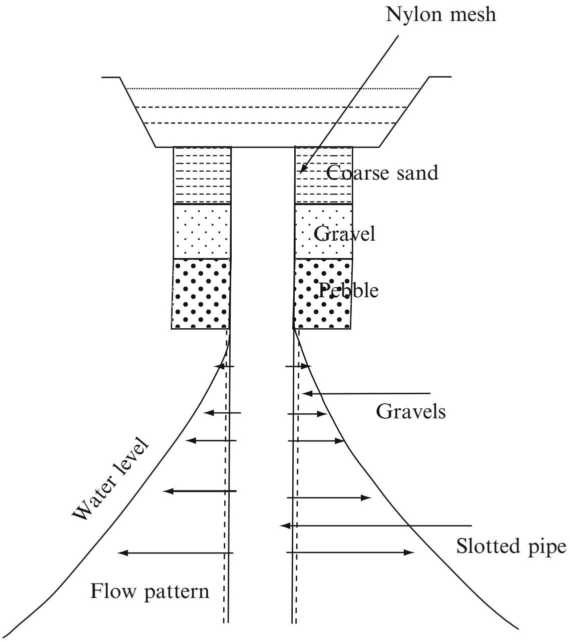
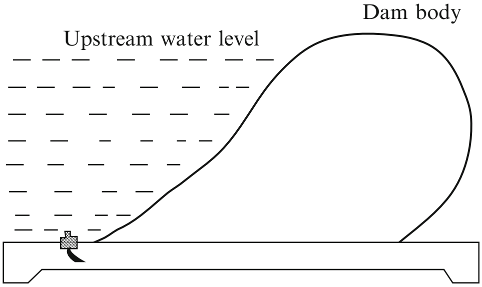


Fig. 11.3 Schematic view (cross-section) of a rubber dam



and deflatable). A unique characteristic of the rubber dam is its ability to function as a reliable minimal maintenance and adjustable-crest gate. The schematic view a rubber dam is given in Fig. 11.3.

Rubber dam have been used in China for over 50 years, and in many other countries as cheaper water conservation structure when compared with conventional gated structure such as barrages. It has wide prospects in the world since they can be used especially for irrigation, hydropower generation, environmental improvement, and recreation purpose. Typically, rubber dam is best suited for low water level and large span.

The rubber dam has the following advantages over other relevant hydraulic structures:

1. Low cost
2. Simple structure
3. Short construction time
4. Can be quickly deflated, thus facilitating discharge during overflow
5. Low resistance to water flow under deflated condition
6. Environmentally friendly
7. Adjustable crest gate
8. Requires minimal maintenance
9. Can have spans as long as 100 m without dividing piers. This provides full width of active cross-section of the river channel to release the flood flow.

In some cases, it may be necessary for rubber dam to retain water at both upstream and downstream. Now-a-days, two-side water retaining rubber dam has been built.

On the basis of the filling medium (whether "air" or "water"), rubber dam can be categorized as:

- Air inflatable
- Water inflatable

11.5.2 Different Parts of a Rubber Dam

The rubber dam system usually comprises four parts:

(a) A rubberized fabric bladder
(b) A concrete foundation, including upstream and downstream cut-off walls, which are used to lengthen the groundwater seepage path and reduce uplift pressures exerted by groundwater
(c) A control house accommodating mechanical and electrical equipment for inflating and deflating the bladder, such as an air blower, water pump, automatic inflation, and deflation mechanism
(d) An inlet/outlet pipe system

The bladder is fixed to the concrete foundation by an anchoring system. Inside the bladder, there are air/water inlet and outlet openings. The control house is located on one side of the dam. It contains a control panel and air compressor/water pump with connecting pipes going from the control house, through the floor to the inside of the dam bladder.

When the bladder is filled with a medium (air, water, or a combination of the two), it rises to retain water. When the medium is released, the bladder collapses flat down to the foundation, completely opening the channel and allowing the free flow of water. The rubber dam can also be set to operate at intermediate heights to meet the need for different upstream and downstream water levels at different times (Tam and Zhang 1999).

A typical rubber dam project is normally composed of three main stages:

- Civil works
- Dam body and anchoring system
- Control system

The civil works stage includes the dam foundation, sidewalls, upstream and downstream wing abutments, upstream and downstream revetments, upstream and downstream cut-off walls, downstream plunge basin, and apron. A water storage pool may be needed to supply water for inflating the bladder in a water-filled dam.

The control system includes inflation, deflation, and monitoring devices. The inflation device supplies the inflation medium to the rubber bladder. An air blower and water pump are used to inflate air- and water-filled dams, respectively, together with valves and other auxiliary devices. The time required for inflation depends on the size and operational conditions of the dam. The normal inflation time is between 10 and 60 min.

The deflation device deflates the rubber bladder by evacuating the filling medium. For safety purposes, both manual and automatic deflation mechanisms are usually incorporated. Exhaust valves are used to deflate the dam manually.

The control system is usually located in a control house, the size of which is about 10 m^2. The control house requires a recess for the mechanic deflation system.

11.5.3 Site Selection for a Dam

The following factors should be taken into account for selecting the most suitable site:

- Hydrology
- Geology
- Geomorphic condition
- Hydraulic condition
- River sediment
- Meteorology
- Construction difficulties or easiness
- Management difficulties or easiness

Although the body of the dam is light, and the load is uniform, the dam site should still be on sound ground, with a concrete foundation in place. The dam site should be in a straight river section where the river flow is smooth and the river-bed and bank slopes are stable. The site should not be in a section where the hydraulic conditions can change abruptly. Adverse hydraulic conditions are the major cause of vibration in rubber dams. Vibration causes abrasion and tearing of the rubber bladder and can result in severe bladder damage. As a result of inappropriate dam site selection, some rubber dams have been unable to function properly and they have had to be demolished. The dam foundation level should be higher than the level of the downstream riverbed to prevent silt and gravel from getting directly under the dam body and increasing the amount of abrasion. Usually, the dam foundation is connected to the downstream riverbed by a steep slope of 1:4 to 1:2.

Relevant Journals

- Journal of Arid Environment (Elsevier)
- Arid Zone Research
- Landscape and Ecological Engineering
- Journal of Soil Water Conservation
- Agricultural Water Management
- Irrigation Science
- Hydrological Sciences Journal
- Journal of Applied Hydrology
- Journal of Applied Irrigation Science (Germany)
- Water Resources Research
- Soil and Tillage Research
- Agronomy Journal
- Hydrology Research

Relevant FAO Papers/Water Reports

- FAO Soils Bulletins 57 (Soil and Water Conservation in Semi-arid Areas)
- FAO Soils Bulletins 54 (Tillage Systems for Soil and Water conservation)
- FAO Water Report 3 (Water Harvesting for Improved Agricultural Production)
- FAO Irrigation and Drainage Paper 10 (Integrated Farm Water Management)

Questions

1. What do you mean by water conservation? Briefly describe the methods of water conservation.
2. Write short note on:
   (a) Cloud seeding
   (b) Seepage control

   (c) Super-absorbents
   (d) Anti-transpirants
3. What is water harvesting? Narrate the historical practices of water harvesting.
4. Discuss the prospects and problems of water harvesting in your area.
5. Briefly describe the various techniques of water harvesting.
6. A small farmer has an area of 1.8 ha. As an engineer you advised him to cultivate this land in dry season through harvesting water by digging a pond near the land. The estimated average percolation and evaporation loss from the pond from the period of water harvesting to start of irrigation (60 days) is 2.0 mm per day. Depth of water needed for 2 irrigations at critical growth stages is 8 cm. What size of pond you will suggest the farmer to dig?
7. In a dry-land agricultural farm, rainwater is harvested in an existing farm pond for dry-season crop cultivation. The volume of water estimated in the pond is 300 m^3. A low water demanding crop is planned to cultivate requiring 120 mm water for irrigation at two water sensitive growth stages. How much area can be irrigated with the stored water?
8. What do you mean by groundwater recharge? Discuss various techniques of groundwater recharge.
9. Do you think that the recharge well is a solution for drought and salinity problem area?
10. Mention the advantages of rubber dam over other relevant hydraulic structure.
11. Name and sketch the various parts of a rubber dam.
12. Discuss the factors to be considered in selecting a site for rubber dam.
13. Evaluate the possibility of constructing rubber dam in your province/state.

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Chapter 12
Economics in Irrigation Management and Project Evaluation

In irrigation management, and broadly applicable to any field, a "*technology*" must offer a high financial rate of return. An investment or intervention is said to be economically efficient when it maximizes the value of output from the resources available. Economic analysis of water use includes the values generated by production activities, the opportunity costs of inputs, and any pertinent costs or benefits that are external to producers and consumers. Economic analysis is helpful in identifying opportunities to increase the net values generated with limited water resources by various techniques/alternatives, and in designing policies that encourage farmers and water agency personnel to improve water management practices in ways that enhance social net benefits. In selecting the best irrigation or drainage project among alternatives, or to judge a single project for its economic viability, several criteria of economic indices are used, which have been described in this chapter with a detail analytical procedure and sample examples.

12.1 Economic Aspects in Irrigation Management and Crop Production

Development of agricultural production is dependent primarily on three basic factors: soil, weather, and water. There may be significant opportunities to increase the net values generated with limited water resources by various techniques/alternatives (improving the distribution of water among farmers, reducing the negative/off-farm effects of irrigation and drainage activities, adopting deficit irrigation, growing low water demand crops, high value (price) crop cultivation, among others). Economic analysis is helpful in identifying those opportunities and in designing policies that encourage farmers and water agency personnel to improve water management practices in ways that enhance social net benefits.

Where resources are scarce, proper planning and decision-making at different levels is essential. In land-limiting situation, maximizing yield per unit of land, and

M.H. Ali, *Fundamentals of Irrigation and On-farm Water Management: Volume 1*, DOI 10.1007/978-1-4419-6335-2_12, © Springer Science+Business Media, LLC 2010

not yield per unit of water, is a more viable objective. In water-scarce areas, water, not land, is the primary limiting factor to improve agricultural production. Accordingly, maximizing yield per unit of water, and not yield per unit of land, is a more viable objective for on-farm water management. It is useful to know how to best utilize the insights and instruments of economics in the design and management of irrigation and other development schemes and interventions.

In many practical problems, we, the engineers, face multiple alternatives in selecting a development plan or project. In such situation, we have to decide the right thing (the best one) – the technology, the structure, project adoption and implementation, etc. among alternatives. Economic merit of a project is judged by comparing projected benefits with projected costs. Under normal condition, an irrigation or drainage development project should be technically feasible, economically viable, and environmentally sustainable. So, we have to consider technical performance, durability, financial involvement (input), outcome/output, environmental aspects, etc. Economic analysis of income and services producing from investment is thus essential. In engineering activities, or activities having a major role of engineers, the engineers are best fitted to analyze such thing due to their background in engineering principles.

12.1.1 Water as an Economic Good

Water has traditionally been regarded as a public good to which no one can be denied access, except some dry areas of the world. Water was available from rainfall, streams, wells, tubewells (bored into aquifers), and diversion of surface flows. Water provision was the responsibility of local people and the investments for this purpose were small. But the situation has been changed. There has been a gradual realization that global stocks are limited and that supply augmentation cannot indefinitely meet ever-increasing demands; and supplies are degraded (polluted and depleted). The growing scarcity and rising cost of water have led to the realization that water has to be allocated and used more efficiently, and to be treated as an economic good. Markets and prices can be used to help ensure sustainable usage, minimize wastage, ensure efficient allocation, and provide incentives for the development of water-efficient technologies, reuse, and recycling.

12.1.2 Typical Criteria of a Technology

In irrigation management, and broadly applicable to any field, a "*technology*" should have the following criteria:

1. *The technology must offer a high financial rate of return.*

A possible increase of 10–20% in yield will not stimulate rapid uptake. This requires a return of 40–100% or more.

2. *The technology must offer a quick payoff.*

For crops this should be in terms of half-year or less. Forestry projects requirelonger periods of time, but the recommendation is "if you want to get trees planted, go for quick-growing species not slow-growing one."

3. *A new technology must involve low risk, preferably reducing the existing risk.*
4. *The technology must have low inputs.*

For the farmer, the technology should require low cash and low inputs of labor. For the government, the technology should avoid recurrent costs, it should have a low import content and maximum use of locally available materials. It should avoid maintenance which requires imported spares or high levels of skill.

5. *The technology should be easy to teach and demonstrate.*

For widespread adoption, there must be the multiplier effect of farmers teaching other farmers. A project that requires large inputs of engineers or of imported machinery will inevitably be restricted to small project areas. A technology that requires a saturation level of extension agents will be restricted to a short period of time or a limited area.

6. *The technology should be socially acceptable.*

Success of a technology depends on the positive and quick response of the users, and willingness to accept it.

12.1.3 Significance of Economic Analysis

The role of economic analysis in the decision-making process is well established. Economic analysis of water use includes the values generated by production activities, the opportunity costs of inputs, and any pertinent costs or benefits that are external to producers and consumers. Economic analysis can be helpful in describing the private (internal) and public (external) costs of an inefficient allocation of resources and in determining strategies for moving toward an efficient allocation.

Commercialization of agriculture is gradually taking place and the farmers are increasingly becoming income sensitive. As the resources are becoming scarce and have alternate use, evaluation of different alternates is prerequisite to achieve economic efficiency. Economic efficiency is achieved when limited resources are used in a manner that generates the greatest net value.

12.2 Basics of Economic Theories and Concepts

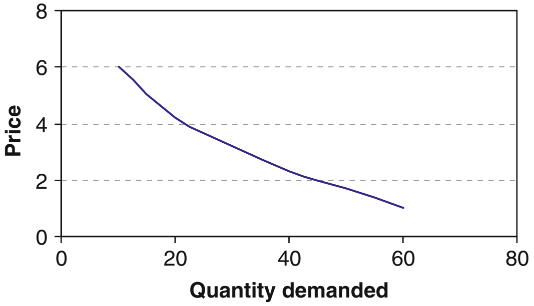
12.2.1 Demand and Supply

The market price of an item is determined by both supply and demand of that item. Demand represents how much (quantity) of an item (product or service) is desired by buyers. Supply represents how much the market can offer. The quantity demanded is the amount of an item that people are willing to buy at a certain price. The quantity supplied refers to the amount of a certain item that the growers are willing to supply in exchange of a certain price.

Graphical presentation of quantity demanded of a good versus price is termed as demand curve (Fig. 12.1). The demand curve indicates negative relationship between price and quantity. The law of demand states that, if all other factors remain equal, the higher the price of a good, the lesser will be the demand for that good because, to buy it, people have to avoid the consumption of other goods that they may value more.

Graphical presentation of quantity supplied of a good versus price is termed as supply curve (Fig. 12.2). The supply curve shows an upward slope, meaning that the higher the price, the higher the quantity supplied. The law of demand states that, if all other factors remains unchanged, the higher the price of a good, the higher will be the supply of that good. This happens because at a higher price, the producer will earn more revenue by selling higher quantity.

Fig. 12.1 Schematic of a demand curve



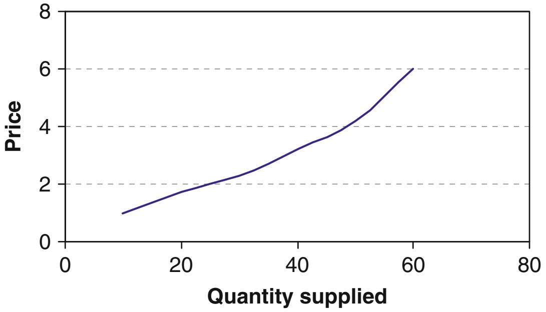


Fig. 12.2 Schematic of a supply curve

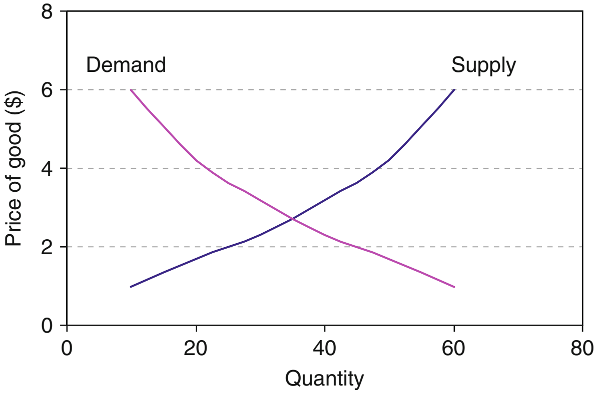


Fig. 12.3 Intersection of supply and demand curves

Therefore, price is a reflection of supply and demand. The relationship between demand and supply underlies the forces behind the allocation of resources. Under perfect market economy condition, the demand and supply theory will allocate resources in the most efficient way possible.

According to principles of economics, the price level of an item is determined by the point at which quantity supplied equals quantity demanded. To illustrate this, consider the case in which the supply and demand curves are plotted on the same graph (Fig. 12.3). In the figure, the price of the good corresponds to that point where the supply and demand curves cross. This point is termed as equilibrium point.

12.2.2 Cost and Revenue Curve

12.2.2.1 Cost Curve

Cost curve is a graphical presentation of the costs of production as a function of total quantity produced (Fig. 12.4). Total cost is the cost of producing some output at some particular rate. Average cost is the cost per unit item.

12.2.2.2 Components of Cost of Production

Total cost of production of a particular item can be divided into two portions:

- Fixed cost, and
- Variable cost

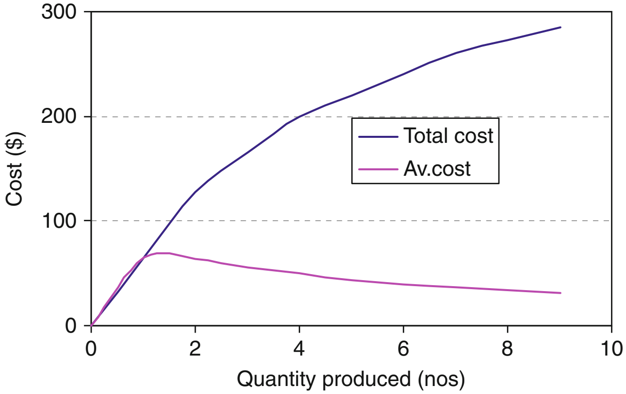


Fig. 12.4 Schematic of total and average cost curves

Fixed cost is the portion of the total cost that requires regardless of the amount of production (small or greater). Examples are rent of office building, salary of security personnel, etc. Variable cost is the rest portion of the total cost that varies with the amount of production. It increases with the increase in production and decreases with the decrease in production. Examples are labor cost, interest on running capital, etc. For economic production process, one must use the least costly combination of inputs for a particular level of output. For a given level of benefits, the optimum mix of output achieves at least cost, or in other words, the maximum level of benefit for a given level of cost.

In economic terms, the cost of water has two broad components:

- The cost of its provision (including both fixed (investment) and variable costs (operation and maintenance)), and
- Its opportunity cost or the production value forfeited/offered in alternate use

These costs are real and unavoidable, and someone has to pay – the user, the taxpayer, or future generations.

12.2.2.3 Revenue or Benefit Curve

Revenue curve or benefit curve is the graphical presentation of the revenue obtained from the quantities produced. The net benefit is the difference between total cost and total income *or* revenue (i.e., net benefit = total revenue − total cost). The vertical difference between cost curve and revenue curve represents the net financial benefit (Figs. 12.5 and 12.6). Maximum net benefit can be determined by constructing cost and revenue curves and by measuring the vertical difference between them. In a free market economy, productively efficient firms use these curves to find the optimal point of production, where they make the profit most.

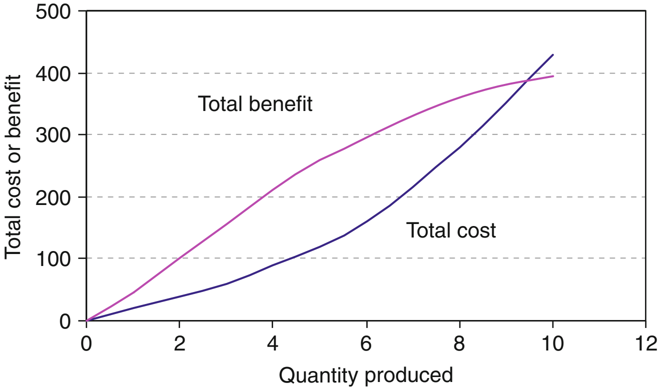


Fig. 12.5 Intersection of total cost and total revenue (or benefit) curves

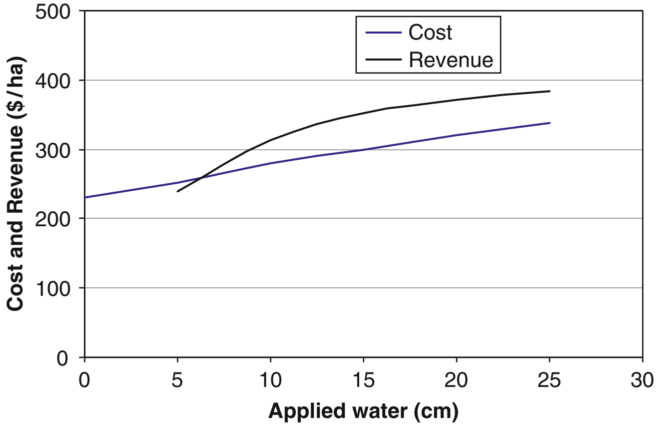


Fig. 12.6 Schematic of cost and revenue curves for irrigated agriculture

The cost and revenue curves help in identifying input conditions for maximizing the net benefit.

12.2.2.4 Features of Cost Curve

The cost curve has several important features:

1. The first is its lower limit, the intercept with the vertical axis, which is associated with capital cost, taxes, insurance, and other fixed costs of irrigation as well as fixed costs of tillage, planting, chemical use, and harvest.

2. The second feature of the cost function is the slope, which represents the marginal variable costs of production. These include the variable costs of irrigation, such as pumping costs, labor, and maintenance. Other costs may also vary with yield, as yield varies with water use. A farmer may adjust his fertilizer or irrigation use in accordance with anticipated crop production, harvesting cost may vary with yield, and so on. All such factors are embodied in the slope of the cost function.

12.2.2.5 Considerations in Calculating Benefit–Cost Ratio

Benefit–cost ratio (BCR) is the ratio of total benefit to the total cost involved. In calculating BCR, all pertinent costs and associated benefits should be taken into account. Benefits and costs can be measured with respect to a goal.

Benefit Stream

One should consider not only direct benefit but also indirect benefits and opportunity cost of the input.

Cost Stream

In addition to fixed cost, variable cost, and opportunity cost, social cost and environmental cost of the resources should also be taken into account.

12.2.2.6 Marginal Cost

Marginal cost measures the change in cost over the change in quantity (or activity) (Fig. 12.7). That is:

$$M_c = \frac{\Delta C}{\Delta Q} \tag{12.1}$$

where M_c is the marginal cost, ΔC is the change in cost corresponding to the change in quantity produced, and ΔQ is the change in the quantity produced.

For example, the total cost of production for 4 ton wheat in 1 ha land is US$500, and it is US$600 for 6 ton. So, we have:

$$\Delta C = 600 - 500 = 100$$
$$\Delta Q = 6 - 4 = 2$$

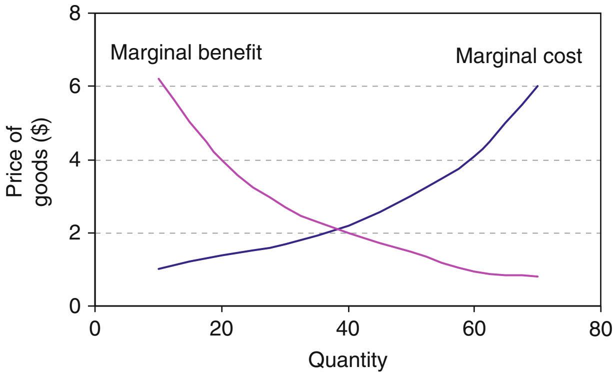


Fig. 12.7 Typical marginal cost and marginal benefit curves

Thus,

$$\frac{\Delta C}{\Delta Q} = \frac{100}{2} = 50$$

Marginal cost of production for the next unit produced is US$50.

Mathematically, marginal cost is the ratio of first derivative of cost and quantity supplied, and it can be expressed as follows:

$$M_\mathrm{c} = \frac{\mathrm{d(TC)}}{\mathrm{d}(Q)} = \frac{\mathrm{d(FC + VC)}}{\mathrm{d}Q} = \frac{\mathrm{d(VC)}}{\mathrm{d}Q} \tag{12.2}$$

where TC is the total cost, FC is the fixed cost, VC is the variable cost, and Q is the quantity of an item supplied. Because, by definition, the fixed cost does not vary with the production quantity, it is eliminated from the equation when it is differentiated.

Marginal cost indicates the increasing or decreasing costs of production. It allows the producers to evaluate how much they actually pay to produce one more (marginal) unit. At each level of production, the marginal cost refers any additional or reduced costs required to produce the next unit.

12.2.2.7 Marginal Benefit

Marginal benefit is a measure of the change in benefits over the change in quantity. That is, at each level of production, the marginal benefit refers any additional or reduced benefits incurred for the production of next unit.

At low levels of production, increase in productivity is easy and marginal cost falls. As production increases, additional gains in productivity become smaller; thus, marginal cost rises because increasing output becomes more expensive. There may be a level of production where marginal cost is higher than the average cost and the average cost will rise for each unit of production after that point. This type of production function is termed as diminishing marginal productivity.

According to the economic theories, the net benefits are maximized upto the point where the benefits added by the last increment of input are equal to the costs of adding that increment of input. Thus, for irrigation practice, irrigation water should be applied until marginal increase in yield is equal to the ratio of marginal benefit to marginal cost.

An economic system is considered efficient at the point where marginal benefit and marginal cost intersect or are equal.

12.2.2.8 Cost and Revenue Function

The relationship between cost and input variable (e.g., irrigation water use), if mathematically defined, is termed as cost function. Similarly, the relationship between revenue and input variable is known as revenue function. When they are plotted in agraph, they are called cost and revenue curve, respectively.

12.3 Economic Considerations in Irrigation and Crop Production

12.3.1 Economic Consequences of Low Irrigation Efficiency

The farm-level economic consequences of low irrigation efficiencies include the loss of productivity due to non-uniform water application, leaching of soil nutrients, and damage from diseases that may arise due to persistent soil moisture conditions. Long-term losses due to soil erosion also may be pertinent, although current farmers may not incur these losses. Farm-level pumping costs will be higher than actual need in regions where farmers use groundwater. In addition, the amount of land that can be cultivated each year will be reduced in regions where annual water supplies are limited.

The external (off-farm) economic consequences of low farm-level irrigation efficiencies include contamination of groundwater and surface water supplies with nutrients and other chemicals, waterlogging and salinization of downstream lands, and sediment loads entering streams and reservoirs. In addition, higher regional expenditure may be required for operating and maintaining regional water delivery systems and for installing regional drainage systems with greater capacity than might be required with higher farm-level irrigation efficiencies.

Poor performance of delivery system generates losses in revenues collected by a water supply agency and reductions in the farm-level productivity of soil and water resources. The internal consequences of poor performance include operational losses of water, damage to canals and other facilities from overtopping and vandalism, waterlogging and salinization within a project area, and higher operational costs of pumping and sediment removal. In addition, poor performance can lead to inequitable distribution of water and income among farmers while reducing aggregate production values.

12.3.2 Economic Efficiency vs. Irrigation Efficiency

The term "efficiency" with a ratio scale that ranges generally from zero to one (0–1) may lead some observers to conclude that higher values approaching unity are preferred. "Irrigation efficiency" refers only to physical quantities of water, in both the denominator and the numerator. It does not capture differences in the value of water in alternate uses. Without consideration of economic variables including input costs, crop prices, and productivity, it is not possible to determine if higher irrigation efficiencies generate greater net economic values than lower ones. Even if a closed irrigation system were operating at nearly 100% overall physical efficiency, substantial economic gains could be made by reallocating water from lower to higher valued uses. The irrigation efficiency may be low in a project area, while it may be high in a river basin if water is recycled. However, water losses in a project area and subsequent recycling may reduce economic efficiency, particularly when large pump lifts are involved.

Economic efficiency implies that the net value of production can be increased by reallocating limited resources or using them more effectively. Economic efficiency in a production setting involves technical and allocative components. Production is technically efficient when the maximum possible output is generated with a given set of inputs, or when a selected output level is produced at minimum cost. Economic efficiency is achieved when limited resources are allocated and used in manners that generate the greatest net value.

The most important difference between economic efficiency and measures of irrigation efficiency is that economic efficiency is a criterion rather than a ratio. Economic efficiency describes the conditions that must be satisfied to ensure that resources are used to maximize the net benefits.

12.3.3 Optimal Levels of Water Use

The optimum level of applied water for a particular situation will be that which produces the maximum profit or crop yield, per unit of land or per unit of water, depending on whether the goal is to maximize profits or food production and whether the most limiting resource is water or land. Therefore, in connection to optimal water use, the following four levels of applied water could be defined as optimal in one sense or another (English 1990):

1. The level of applied water at which crop yield per unit of land is maximized.
2. The level at which yield per unit of water is maximized.
3. The level at which income per unit of land is maximized.
4. The level at which income per unit of water is maximized.

English (1990) derived equations for each of the above four optimum application levels. The derivation was based on a quadratic form of production function. As the production and cost functions depend on a number of local factors, a particular form of production and cost function may not exist in real-world situations; hence, deviations from the optimum levels may occur. So, for the potential benefits of irrigation and the range of profitable deficits under different circumstances, it is advisable to analyze the cost and return from field experimental data, and to derive the optimum levels from the cost and revenue graphs. From the graphs of cost and revenue under different situations, the decision maker can make an exact prescription for the amount of water to apply.

12.3.3.1 Land-Limiting Condition

Under some circumstances, available land for cultivation may be limited, but the available water may be abundant. If land is limited, but there is no opportunity to expand irrigated acreage even if more water is available, this is a land-limiting case. Under such condition, the optimum irrigation strategy would be to apply that amount of water which would maximize the net income incurred from each unit of land.

12.3.3.2 Water-Limiting Condition

An area with limited water and abundant land, and the farm in question has an opportunity to irrigate additional land if water becomes available; this is a water-limiting case.

Crop production is often constrained by a shortage of irrigation water. In such water-limiting conditions, the water saved by reduced (or deficit) irrigation of one piece of land might be used to irrigate additional land, thus increasing farm income. Thus, under water-limiting conditions, the optimum strategy would be that which generates maximum net income from each unit of water.

12.3.4 Opportunity Cost of Water

The opportunity cost of water is its value in other uses that may include production of alternative crops or use in municipal, industrial, or recreational activities. The opportunity cost of water must be considered when seeking an efficient allocation of scarce water resources. In water-limiting conditions, if the water saved by reducing the depth of irrigation is used to bring additional land under irrigation (with the same profit per unit of land), the total farm profit is increased still more. The net income from the additional land represents the opportunity cost of water.

12.3.5 Farm-Level Profit Maximization

Farmers seeking to maximize profits will use water and other variable inputs at levels where the incremental value generated is equal to the incremental cost. Farmers will also choose cropping patterns that maximize the net returns, over time, subject to their resource endowments, relative input and output prices, and marketing opportunities. In regions where farm-level water supplies are scarce, relative to available land, farmers will choose crops that maximize the net returns to their limited water supplies. If land is scarce, while water is relatively abundant, farmers will choose crops that maximize the net returns per unit of land. Farm-level choices regarding water management will vary with the cost and availability of water and of methods for improving irrigation efficiency.

12.3.6 Maximizing Social Benefit

The public's goal regarding water resources can be described as maximizing the present value of net benefits. The benefits include farm-level net returns, opportunity costs of water, and externalities. Externalities are the off-farm effects of irrigation and drainage that impose costs or benefits on other farmers or public. Positive externalities involve benefits such as the generation of usable surface runoff or the provision of water supply to a desirable wetland area. Negative externalities involve near-term and long-term damages caused by surface runoff and deep percolation. Examples of negative externalities caused by irrigation and drainage include the water-logging and salinization that develop in tail-end areas of an irrigation system when head-end farmers overirrigate. Another example is the impact of localized water-logging caused by continuous flooding of the rice fields. Crop yields on non-rice fields can be reduced by rising water-table or water-logging caused by excessive seepage and percolation on adjacent rice fields.

12.4 Mathematical Formulation for Minimum Cost or Maximum Profit

12.4.1 Minimizing Cost

In many irrigated areas, the optimum allocation of limited water resource requires to achieve a minimum-cost or maximum-profit objective. To illustrate such perspective, let us consider a cost function as follows:

$$C = a_1 y + b_1 y + \frac{c_1}{y} + k \tag{12.3}$$

where y is the variable; and a_1, b_1, c_1, k are the coefficients, which are positive or equal to zero.

To find the minimum cost-point, we have to differentiate the function, set it equal to zero, and solve for y. That is,

$$\frac{\mathrm{d}C}{\mathrm{d}y} = a_1 + b_1 - \frac{c_1}{y^2} = 0$$

Then, $y = \sqrt{c_1/(a_1 + b_1)}$

To ensure that this is the minimum value rather than maximum value, we have to compute second derivative $(\mathrm{d}C^2/\mathrm{d}y^2)$. It will be minimum if the $\mathrm{d}C^2/\mathrm{d}y^2$ is positive, and maximum if $\mathrm{d}C^2/\mathrm{d}y^2$ is negative.

In the above case, $\mathrm{d}C^2/\mathrm{d}y^2 = 2c_1/y^3$

It has a positive value for all positive values of c_1. Hence, the minimum cost-point is at $y = \sqrt{c_1/(a_1 + b_1)}$.

12.4.2 Maximizing Net Benefit

The cost and gross income functions of an irrigated production system can be formulated, taking into consideration the associated variables. Then, the net income or benefit (I_{n}) is:

$$I_n = \text{Gross income} - \text{Total cost}$$

Following the above principle, to find out the desired input rate (here, water) for maximum net benefit, we have to differentiate the net income function and set it to zero. That is,

$$\frac{\mathrm{d}I_n(w)}{\mathrm{d}w} = 0$$

Then, we have to solve the equation for target variable.

12.5 Different Water Productivity Indices in Irrigation Management

12.5.1 Water Productivity (E_{ET})

Water productivity (also termed as "water use efficiency" (WUE)) is defined as the ratio of yield to the consumptive water use, that is,

$$E_{\mathrm{ET}} = \frac{Y}{\mathrm{ET}} \tag{12.4}$$

where Y is the seed yield (t/ha) and ET is the crop water use or evapotranspiration (cm).

12.5.2 Productivity of Irrigation Water (E_{ir})

Productivity of irrigation water (E_{ir}) is defined as the ratio of yield to the irrigation water applied, that is,

$$E_{\mathrm{ir}} = \frac{Y}{\mathrm{IR}} \tag{12.5}$$

where IR is the irrigation water applied (cm).

12.5.3 Marginal Productivity of Irrigation Water

Technically, the marginal productivity of a particular resource is defined as the addition to the gross output caused by an addition of 1 U of that resource while other inputs are held constant. Marginal productivity of irrigation water ($\mathrm{MP}_{\mathrm{ir}}$) was calculated as:

$$\begin{gathered}(\mathrm{MP}_{\mathrm{ir}}) = \frac{\Delta Y}{\Delta \mathrm{IR}} \\ = \frac{\text{Marginal increase in yield}}{\text{Marginal increase in irrigation water}}\end{gathered} \tag{12.6}$$

12.6 Economic Analysis Under Different Resource Constraints and Different Budget Considerations

12.6.1 Analysis Under Different Budget Consideration

12.6.1.1 Partial Budget Analysis

Partial budget analysis is done by taking into consideration only the cost of the variable (say, irrigation or fertilizer) for the cost estimation. The salvage value of the products is considered for benefit estimation.

12.6.1.2 Full Budget Analysis

In this analysis, total cost of production is considered for cost estimation.

Partial and full budget analyses can be performed for both land-limiting (without considering opportunity cost of water) and water-limiting (considering opportunity cost of water) conditions.

12.6.2 Analysis Under Different Resource Constraints

12.6.2.1 Land-Limiting Condition

Considerations and Procedures of Economic Analysis for Land-Limiting Condition

In full budget economic analysis for different irrigation management strategies, the cost items may be categorized as following heads for analytical advantages:

1. Cost of land preparation (power tiller)
2. Cost of seed
3. Cost of fertilizer
4. Cost of irrigation
5. Cost of insecticide
6. Cost of human labor
7. Land use cost
8. Interest on operating capital

Human labor requirement in irrigation studies consists of cleaning the land from weed (during land preparation), sowing, weeding and thinning, insecticide spraying, harvesting, carrying to the threshing place, threshing, and cleaning.

Total cost of production can be grouped again into:

1. Land use cost
2. Operation cost
3. Interest on operating capital

Land Use Cost

Land use cost may be estimated using any one of the following three alternative methods:

1. Interest on the value of land for concern period.
2. Foregoing income from alternative use, i.e., opportunity cost of land.
3. Seasonal rental amount or leased value of the land used.

Operation Cost

The operating capital consists of the cost of tillage (or hiring of a power tiller), seed, fertilizer, irrigation, insecticide, and human labor. If the farmers hold equipments or tools (such as power tiller or plough, yoke, pump, sprayer, etc), the operating cost should be the cost of fuel in addition to rental charges. The rental amount may be taken from local rent rate or can be gauged from depreciation value.

Interest on Operating Capital

The operating capital actually represents the average operating costs over the period because all costs are not incurred at the beginning or at any fixed time. It is assumed that if the farmers kept the money in a commercial bank for the period, they would have received an income in the form of interest money. Interest on operating capital is to be charged for the period of crop at the rate of local bank interest. Generally, it is estimated by using the following formula:

$$\text{Interest on operating capital}(R) = \left(\frac{\text{Operating capital}}{2}\right) \times \text{Rate of interest} \\ \times \text{Time considered (year)}$$

That is,

$$R = \frac{C}{2} \times r \times N \tag{12.7}$$

where C is the operating cost, r is the interest rate, and N is the time in year.

Gross Return Calculation

Gross return per hectare is calculated by multiplying the total amount of product and by-product by their respective market prices.

Net Return Calculation

Net return is calculated by subtracting the total cost from the gross return. For a series of similar data, the net return can be calculated from the cost and revenue curve, derived from unit resource (land or water). In land-limiting case, the cost and gross revenue per unit of land are plotted as a function of applied water. In water-limiting case, the cost and gross revenue per unit of water are plotted as a function of applied irrigation strategies. The vertical distance between cost and revenue curves represents the net return.

12.6.2.2 Water-Limiting Condition

Analyses of different irrigation strategies are performed taking into consideration the opportunity cost of irrigation water. Water saved through a particular deficit strategy is used to put additional land into production. The potential increase in farm income from additional land is an opportunity cost of the water. Cost and revenue are calculated by following the same procedure as for land-limiting condition.

12.6.3 Example on Economic Analysis for Different Irrigation Management Strategies

Example 12.1. In a trial of irrigation management strategies in wheat production, the following information is available:

Irrigation strategy (ID)	Frequency of irrigation under the strategy	Total water applied (cm)	Grain yield (t/ha)	Straw yield (t/ha)
I_1	4	24	3.70	7.00
I_2	3	18	3.57	6.60
I_3	2	12	3.40	6.10
I_4	1	6	3.03	6.29
I_5	0 (non-irrigated)	0	1.88	3.90

Market price of wheat: 154 US$/t
Market price of straw: 8 $/t
Cost per irrigation: 32 $/ha
Land use cost (rent of land for 6 months): 114 $/ha

Power tiller cost (for land preparation): 46 \$/ha
Cost of fertilizer: 51 \$/ha
Cost of seed: 30 \$/ha
Cost of insecticide: 8 \$/ha

Human labor requirement (per hectare):
Land cleaning – 7 nos
Sowing (manual) – 2 nos
Weeding and thinning – 37 nos
Insecticide spray – 2 nos

Harvesting, carrying:
Irrigated plots – 22 nos
Non-irrigated plot – 15 nos

Threshing, cleaning:
Irrigated plots – 37 nos
Non-irrigated plot – 25 nos

Cost of human labor (per person per day): 2 \$
Interest rate: 10%

Calculate:

1. Partial budget analysis under both land- and water-limiting conditions.
2. Full budget analysis under both land- and water-limiting conditions.
3. Propose best irrigation management option.

Solution. 1 *Partial budget*

(a) *Under land-limiting conditions*

Cost and revenue under different strategies can be summarized as follows:

Irrigation frequency	Seed yield (t/ha)	Straw yield (t/ha)	Revenue from wheat and straw (\$)	Total irrigation cost (\$)	Benefit (\$)
4	3.7	7	626	128	498
3	3.57	6.6	603	96	507
2	3.4	6.1	572	64	508
1	3.0	6.29	512	32	480
0	1.9	3.9	324	0	324

Notes: Revenue = (seed yield × price of seed) + (straw yield × price of straw), total irrigation cost = irrigation frequency × cost per irrigation, and benefit = revenue – total irrigation cost

(b) *Under water-limiting conditions*

Total cost and revenue under water-limiting conditions (considering the opportunity cost of water) are summarized below:

Irrigation strategy	Irrigation frequency (nos)	Opportunity for irrigating additional area compared with 4 frequency (ha)	Total area (ha)	Total grain yield (t)	Total straw yield (t)	Revenue from grain and straw ($)	Total irrigation cost ($)	Benefit ($)
I_1	4	0	1	3.7	7.0	626	128	498
I_2	3	0.33	1.33	4.75	8.78	801	128	674
I_3	2	1	2	6.80	12.2	1,145	128	1,017
I_4	1	3	4	12.0	25.2	2,049	128	1,921

Lower frequency of irrigation facilitates additional land under cultivation, and produces more grain and straw, and hence more revenue.

2. *Full budget analysis*
   (a) *Under land-limiting conditions*

Operating cost estimation

Total operating cost is the sum of power tiller cost (land preparation); fertilizer, seed, insecticide cost, and human labor cost. The summary is given below:

Irrigation frequency	Area (ha)	Land preparation cost ($)	Fertilizer cost ($)	Seed cost ($)	Insecticide cost ($)	Irrigation cost ($)	Human labor cost ($)	Total operating cost ($)
4	1	46	51	30	8	128	214	477
3	1	46	51	30	8	96	214	445
2	1	46	51	30	8	64	214	413
1	1	46	51	30	8	32	214	381
0	1	46	51	30	8	0	176	311

Notes: Human labor cost = number of human labor required × unit labor cost, total irrigation cost = irrigation frequency × cost per irrigation

Full cost and benefit analysis

Irrigation ID	Irrigation frequency (nos)	Total area (ha)	Grain yield (t)	Straw yield (t)	Total revenue ($)	Total operating cost ($)	Interest on operating capital ($)	Land use cost ($)	Total cost ($)	Net benefit ($)	B–C ratio
I_1	4	1	3.7	7	626	477	12	114	603	23	1.04
I_2	3	1	3.57	6.6	603	445	11	114	570	32	1.06
I_3	2	1	3.4	6.1	572	413	10	114	537	35	1.07
I_4	1	1	3.0	6.29	512	381	10	114	505	8	1.02
I_5	0	1	1.9	3.9	324	311	8	114	433	−109	0.75

Notes: Interest on operating capital is calculated using the following formula:

Interest on operating cost $= \frac{(\text{Operating cost} \times \text{Interest rate} \times \text{Time period in year})}{2}$

Here, time period (for wheat) = 0.5 year; given interest rest = 10%

(b) *Under water-limiting conditions*

Operating cost estimation

The calculation summary is given below:

Irrigation frequency	Opportunity for additional area (ha)	Total area ($)	Land preparation cost ($)	Fertilizer cost ($)	Seed cost ($)	Insecticide cost ($)	Irrigation cost ($)	Human labor cost ($)	Total operating cost ($)
4	0	1	46	51	30	8	128	214	477
3	0.33	1.33	61	68	40	11	128	285	592
2	1	2	92	102	78	16	128	428	844
1	3	4	184	205	315	32	128	856	1,720

Notes: Here, "opportunity" means possibility for irrigating additional area with a particular strategy (I_2 to I_4, 3 to 1 frequency) compared with I_1(4 frequency) strategy, with the same frequency (for the particular frequency) policy

Full cost and benefit analysis

The calculation summary is given below:

Irrigation ID	Irrigation frequency (nos)	Total area including opportunity (ha)	Total grain yield (t)	Total straw yield (t)	Total revenue ($)	Total operating cost ($)	Interest on operating capital ($)	Land use cost ($)	Total cost ($)	Net benefit ($)	B–C ratio
I_1	4	1	3.7	7	626	477	12	114	603	23	1.04
I_2	3	1.33	4.75	8.8	801	592	15	152	759	43	1.06
I_3	2	2	6.8	12.2	1,145	844	21	228	1,093	52	1.05
I_4	1	4	12	25.2	2,049	1,720	43	456	2,219	−170	0.92

3. *Decision on best irrigation management option*

Under both land- and water-limiting conditions, the irrigation strategy I_3 produced the highest net benefit. Hence, this strategy may be practiced under the resource limitations.

12.7 Economic and Financial Analysis of Development Projects

The purpose of economic analysis of projects is to increase the net output measured at economic prices in the national economy. An investment or intervention is said to be economically efficient when it maximizes the value of output from the resources available. In economic and financial decision making, we need the following types of project decision for which criteria are needed:

1. Testing the economic viability of a project.
2. Choice of the best among project alternatives.
3. Choice of the least-cost option for achieving the same benefits.

12.7.1 Different Economic and Financial Indices and Related Terminologies

12.7.1.1 Present and Future Values

Present value tells the current worth of a future sum of money. Future value gives one the future value (at a future date) of cash that one have now. Both of this has practical implication. For example, you have \$1,000 saving and will start to save \$500 per month in an account that yields 12% per year. You will make your deposit at the end of each month. You want to know the value of your investment in 5 years or the future value of your savings account. For a multiyear project, future values of the present values (and near future cash flows, if any) are calculated at the end of the project life.

12.7.1.2 Benefit–Cost Ratio

For multiphase or multiyear projects, BCR is defined as the ratio of the present value of the economic benefits stream to the present value of the economic costs stream, each discounted at the economic opportunity cost of capital. The ratio should be greater than 1.0 for a project to be acceptable. An irrigation or drainage system is considered to be economic only if the *B–C* ratio is greater than one. The BCR helps in identifying the least-cost option for achieving the same benefits.

12.7.1.3 Least-Cost Analysis

Least-cost analysis aims at identifying the least-cost project option for supplying output to meet forecasted demand. This method applies to projects where the benefits can be valued or to projects where the benefits take the form of a single commodity. Least-cost analysis involves comparing the costs of the various mutually exclusive, technically feasible project options and selecting the one with the lowest cost. For multiyear projects, the alternative with the lowest present value of costs (for desired output) is the least-cost alternatives. For example, it may be that the cheapest way of increasing water supply is through more efficient management of the existing supply rather than through augmenting capacity.

12.7.1.4 Cost Effectiveness

In some cases, the benefits or outcomes of a project cannot be valued (or directly measured), but can be quantified or have a specific outcome. For example, in a pollution control project, the outcome is pollution control (having specific quality or grade) with a specific cost. To attain a specific grade of pollution control, different methods or techniques can be employed and their cost may be different. Cost-effectiveness analysis is an analysis that seeks to find the best alternative activity, process, or intervention that minimizes resource use to achieve a desired result. Alternatively, where resources are constraint, it seeks to identify the best alternative that maximizes outputs/results for a given application of resources.

A measure of the cost effectiveness is obtained by measuring costs against outcome (average incremental economic cost). The cost effectiveness ratio – the cost per unit change in quality (improving certain quality, lessening hazardous effect, etc.) for each of the alternative methods is compared. The technique or method that needs minimum cost to attain targeted outcome is most cost effective. Analysis of cost effectiveness allows choosing the best one evaluating various options.

There may be circumstances where the project alternatives have more than one outcome. In order to assess the cost effectiveness in such cases, it is necessary to devise a testing system where the outcomes of different dimensions can be added together. It is also necessary to select some weights for adding the different dimensions reflecting their relative importance in relation to the objectives of the project. Such a use of cost-effectiveness analysis is called weighted cost-effectiveness analysis.

12.7.1.5 Opportunity Cost

The opportunity cost can either be how much one can earn by investing the money in some place or how much interest one would have to pay if he/she borrowed money.

12.7.1.6 Initial Investment

It is the investment made at the beginning of a project. The initial investment may include hardware (cost of buying and installing the machine, structural setup), software, startup costs, licensing fees, etc. Since most of the projects involve initial cash outflow, its value is usually negative.

12.7.1.7 Salvage Value

It is the money that can be gained by selling the hardware or instruments at the end of the project. If there is, the amount would be added to the income amount, normally at the last year of the project.

12.7.1.8 Nominal and Real Values (Cost, Benefit, and Interest Rate)

The real value is one where the effects of inflation have been factored, whereas a nominal value is one where the effects of inflation have not been accounted for.

To account for inflation, either real or nominal value may be used, but with consistently. That is, nominal costs and benefits require nominal discount rates, and real costs and benefits require real discount rates.

The real interest is one where the effects of inflation have been factored in, whereas a nominal interest is one where the effects of inflation have not been accounted for. That is,

$$\text{Real interest rate} = \text{Nominal interest rate} - \text{Inflation}$$

Inflation is generally positive. If so, the real interest rate is lower than the nominal interest rate. If the inflation rate is negative (i.e., deflation), then the real interest rate will be lager than the nominal interest rate.

12.7.1.9 Income Stream or Cash Flow

An income stream is a series of amounts of money. Each amount of money comes in or goes out at some specific time, either now or in the future. Sample example of an income stream is given below:

Year	0	1	2	3	4	5
Income amounts	−$2,000	$500	$600	$700	$600	$600

The net cash flow for each year of the project is the difference between revenue (or benefit) and cost. All the amounts in the income stream are net income, meaning that each is revenue minus cost, or income minus outgo. In the year 0, the cost exceeds the revenue by $2,000. Negative income is cost, or outgo, which represent the cost of buying and installing the machine. In the years 1 to 5, the revenue exceeded the cost. The investment evidently has no salvage value. If there were, the amount that could be realized from the sale would be added to the income amount for the year 5. For simplicity, the cash flow in the above example is at 1-year intervals, but real-time investments can have cash flow (income minus expenses) at irregular times. But the principles of evaluation are the same for all cases.

12.7.1.10 Internal Rate of Return

Internal rate of return (IRR) is traditionally defined as the discount rate at which net present value (NPV) is equal to zero. It is the projected discount rate that makes the NPV of a project equal to zero. It is one of the capital budgeting methods used by firms to decide whether they should make long-term investments. It helps making decision about which project is most economical for a particular situation.

12.7.1.11 Discounting

Discounting is a procedure developed by economists to evaluate investments that produce future income. It is the processwhereby the values of future effects are adjusted to render them comparable to the values placed on current costs and benefits. It is accomplished by multiplying the future value(s) with the discount factor.

12.7.1.12 Discount Rate

A percentage rate representing the rate at which the value of equivalent benefits and costs decreases in the future compared with the present. The discount rate is used to determine the present value of the future benefit and cost streams.

The rate can be based on the alternative economic return in other uses given up by committing resources to a particular project, or on the preference for consumption benefit today rather than later. The economic NPV is generally calculated for each project alternative using the bank interest rate (~8–10%).

12.7.1.13 Compounding

It is the process whereby the values of present effects are adjusted to render them comparable to the values placed on future consumption, costs, and benefits.

12.7.1.14 Discounted Cash Flow

The discounted cash flow (DCF) approach describes a method to value a project or an entire company using the concepts of the time value of money. It is widely used in investment finance, real estate development, corporate financial management, and other development projects. All future cash flows are estimated and discounted to give them a present value. DCF includes the present value (PV) and the IRR methods of analyzing cash flows. The DCF provides insight into financial management.

The DCF formula is derived from the future value formula for calculating the time value of money and compounding returns.

$$\mathrm{FV} = \mathrm{PV}(1 + i)^n \tag{12.8}$$

where FV is the future value, PV is the present value, i is the interest rate (or time value of money), and n is the number of years.

For single cash flow in one future period, DCF equation can be expressed as:

$$\mathrm{DPV} = \frac{\mathrm{FV}}{(1+r)^n}$$

where DPV is the discounted present value of the future cash flow (FV) and r is the discount rate.

In case of cash flows in multiple time periods, discounted present value is the sum of the individual present values, expressed as:

$$\mathrm{DPV} = \sum_{t=0}^{N} \frac{\mathrm{FV}_t}{(1+r)^t} \tag{12.9}$$

where t is the time period (year number from the present year).

12.7.2 Expression of Cost and Benefit

In different projects, investment (or input requirement) and the return (or outcome) do not follow the same time. Thus, they are not directly measurable. To overcome this problem, the inputs and outputs are converted to an equivalent amount.

There are different ways to express and compare costs and benefits that occur in multiple time periods on a consistent basis. Procedures for calculating cost and benefit that occur in more than one time period are:

(a) Net future value (NFV).
(b) Annualized value.
(c) Net present value (NPV).

Discounting places all costs and benefits at the present time period; annualization spreads them smoothly over time; and accumulation places them at a future time. Among the three procedures, NPV method is widely used.

(a) *Net future value*

Net future value (NFV) is a way of rendering cost and benefit that occur in more than one time period. It is the total future value of all cash flows. It is an estimate of what the principal will become over time. For example, assuming a compound rate of 8% and a present value of \$5,000, 10 years from now, NFV will be \$10,794.62.

The NFV value of a projected stream of current and future costs and benefits is obtained by multiplying the benefits and costs in each year by a time-dependent weight, d_t, and adding all of the weighted as follows:

$$\mathrm{NFV} = d_0\mathrm{NB}_0 + d_1\mathrm{NB}_1 + d_2\mathrm{NB}_2 + \cdots + d_{n-1}\mathrm{NB}_{n-1} + d_n\mathrm{NB}_n \tag{12.10}$$

where NB_t is the difference between benefits and costs that accrue in year t and the accumulation weights (also termed as compound factor), d_t, is given by:

$$d_t = (1 + r)^{(n-t)} \tag{12.11}$$

where r is the discount rate. Thus, the (12.11) can be written as:

$$\mathrm{NFV} = \sum_{t=0}^{n} \mathrm{NB}_t(1 + r)^{(n-t)} \tag{12.12}$$

(b) *Annualized values*

For example, in the absence of a discount rate, a cost of US\$1,000 becomes US \$2,000 at the end of the first year, US\$3,000 at the end of the second year, and US \$4,000 at the end of the third year. From this, it can be said to cost US\$1,000 per year in annualized costs over the 3-year period. Costs and benefits may be annualized separately by using a two step process. Comparing annualized costs to annualized benefits is equivalent to comparing the present values of costs and benefits. To compare average cost effectiveness among the alternative policy options, divide the annualized cost by annualized benefit (such as cost per 100 m^3 water loss avoided and cost per meter groundwater depletion avoided).

(c) *Net present value*

NPV is the difference between the present value of the benefit stream and the present value of the cost stream for a project. The word "net" in "net present value" indicates that the calculation includes the initial costs as well as the subsequent cost and benefit.

Costs and benefits of a development project or a policy frequently occur at different times. The NPV of the time-phased costs over the economic life of an investment project is the best single-number measure of its life-cycle cost.

If we assume that income comes (benefit) or goes (cost) in annual bursts, the NPV of a projected stream of current and future costs and benefits is obtained by multiplying the benefits and costs in each year with a time-dependent weight, d_t, and adding all of the weighted as follows:

$$\begin{aligned}\mathrm{NPV} &= \mathrm{NB}_0 + d_1\mathrm{NB}_1 + d_2\mathrm{NB}_2 + \cdots + d_{n-1}\mathrm{NB}_{n-1} + d_n\mathrm{NB}_n \\ &= \mathrm{NB}_0 + \sum_{t=1}^{n} d_t\mathrm{NB}_t\end{aligned} \tag{12.13}$$

where NB_t is the difference between benefits and costs that accrue in year t, n is the final period in the future ($n = t$), and the discounting weight (also termed as discount factor), d_t, is given by:

$$d_t = \frac{1}{(1+r)^t}$$

where r is the discount rate. Thus, the equation can be written as:

$$\text{NPV} = \text{NB}_0 + \sum_{t=1}^{n} \frac{\text{NB}_t}{(1+r)^t} \tag{12.14}$$

As the initial investment is a cost, it is treated as negative benefit.
That is,

$$\text{NPV} = (-\text{Initial investment}) + \frac{\text{Net cash flows at year } t}{(1+r)^t}$$

12.7.3 Analysis of NPV

Analysis of NPV requires four basic steps:

- Forecast the benefits and costs in each year.
- Determine a discount rate.
- Use a formula to calculate the NPV
- Compare the NPVs of the alternatives.

12.7.3.1 Step 1: Forecasting the Benefits and Costs

Accurate forecasting of future costs and benefits can be the most difficult and critical step in NPV and as a whole in project financial analysis. All possible costs and benefits of the proposed project should be taken into account, including non-monetary costs and benefits. A sunk cost should be ignored in the analysis. It is the cost that will be same regardless of what decision is made. For example, cost for survey of the project area.

Cost Forecasting

The costs should include:

- Input cost.
- Operational cost.
- Maintenance cost.
- Opportunity cost of the inputs/resources.
- Uncertain cost.

Input cost

All sorts of input costs (both fixed and variable) should be considered in analysis. Salaries of the farm manager and other staff, fee of the consultant, etc. fall under this category.

Opportunity cost

The opportunity cost of a project is the potential benefits that are lost by selecting the project. More specifically, it is equal to the net benefit that is to be achieved from alternate use of the resources (capital, human resources, or other major inputs). For example, a project has been proposed to develop an agricultural farm for crop production over a land of 100 ha. If the farm is not developed, the farmer will get 5,000 US$ per annum as hire for cattle grazing without any investment. Now, $5,000 is to be added to the total cost as opportunity cost. If this opportunity cost is not included as cost in project analysis, then some proposals may appear to be better because they are using existing resources free.

Operational cost

This includes salary of the laborers, fuel for the tractor, fertilizers, insecticides, etc.

Maintenance cost

This category includes repair cost of the farm instruments, computers, cars, etc.

Uncertain cost

Sometimes it is difficult to estimate the cost because they are dependent on an unpredictable environment. In such uncertain case, still it is possible to make an estimate (expected value).

12.7.3.2 Step 2: Determination of Discount Rate

The discount rate converts the stream of future costs and benefits into their value today. The process of discounting is needed due to the time value of money and inflation, and therefore discount rate should be determined based on the aforementioned two factors. For convenience, sometimes it is taken equal to the bank interest rate.

Consistent decision making requires that the same discount rate be used for both benefit and cost, if net benefit is not used. Moreover, the same discount rate must be used for different alternative options.

Impact of Discount Rate on NPV Estimates

In general, the NPV estimate varies with the discount rate. But under some circumstances, the NPV may be very sensitive to discount rate. When costs and benefits of a project are largely constant over the time period, discounted costs and benefits will produce almost the same conclusion regarding the project acceptance or rejection. Only, the higher discount rate will reduce the NPV. Discount rate may significantly affect the NPV estimates when there is a substantial difference in the timing and amount costs and benefits. We may consider a project where all the costs are incurred at the starting (or first year) of the project, but the benefits will occur over 50 years period. In such cases, the costs are not discounted but the benefit will do. Hence, the NPV here will depend critically on the discount rate used.

12.7.3.3 Step 3: Calculation of NPV

At first, calculate the net benefit for each year by subtracting the cost from the benefit. Then, calculate the NPV for the net benefit of each year using the formula given below:

$$\mathrm{NPV}_n = \frac{\mathrm{NB}_n}{(1+r)^n} \tag{12.15}$$

where NPV_n is the net present value for the year n, NB_n is the net benefit for the year n, and n is the chronological serial number of the year in the cash flow series for which the NPV is calculated.

In the above equation, the time-dependent weighting factor, $1/(1+r)^n$, is termed as discounting factor. In NPV calculation, for simplicity, it is assumed that the discount rate will not change over the life of the project.

Sum up the NPVs to get total NPV. Similarly, calculate NPVs for the alternatives. The procedure has been explained below with sample examples.

The main limitation of NPV analysis is the difficulty of accurately forecasting future costs and benefits.

12.7.3.4 Step 4: Compare the NPVs of the Alternatives

The NPVs of the alternatives are compared and a decision is taken.

The NPV calculated at the bank's discount rate should be greater than zero for a project to be acceptable. A positive NPV means the investment is better. A negative NPV means the alternative investment, or not borrowing, is better.

12.7.4 The NPV Curve

The NPV curve shows the relationship between the discount rate and the NPV for a range of discount rates (Fig. 12.8). With the net-positive cash flows, NPV decreases from maximum at a 0% discount rate and converges to zero as it increases. Once NPV crosses zero, where IRR is determined, NPV is negative at all discount rate s.

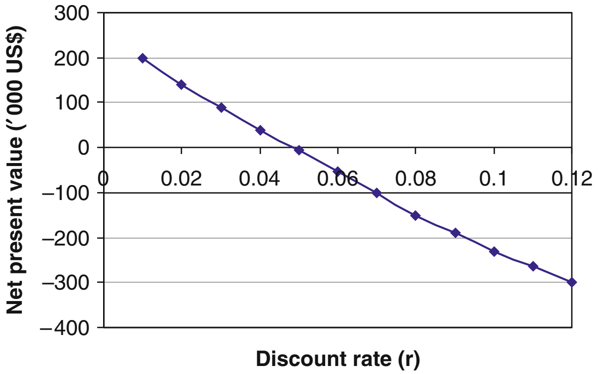


Fig. 12.8 The NPV curve

The curve shows the NPV for a discount rate of 0–2. The curve crosses the horizontal line (indicating NPV = 0) between 0.04 and 0.06. So the IRR is between 0.04 and 0.06 (nearly at 0.05). Thus, the IRR is 0.05.

The NPV curve can be represented by the formula:

$$\mathrm{NPV} = I_0 + \frac{I_1}{1+r} + \frac{I_2}{(1+r)^2} + \cdots + \frac{I_n}{(1+r)^n} \tag{12.16}$$

where I_0 is the initial investment, I_i is the income amount for the specific year i ($i = 0$ to n), and r is the discount rate. This is similar for the NPV for annualized costs and revenues with a constant discount rate.

12.7.5 Discounting/Compounding Formula Under Different Perspectives

The following situations of cash flow are considered here for mathematical derivation:

(a) Single installment/cash flow of money
(b) Uniform annual cash flow
(c) Discrete non-uniform annual cash flow

12.7.5.1 Single Installment/Cash Flow of Money

In this case, the aim is to convert the amount at one date to an equivalent value at another date. More specifically, the present value is converted to a future value (compounding), or the future value is converted to an equivalent present value (discounting).

Single Installment Compounding

Let us assume that P is the present income (or cost, investment) amount and we want to know its future value after n years (that is, what amount it will be). To do this, we have to know the rate of return per year of the investment. Let r is the rate of return (in percent) per year of the investment for the prevailing condition. After 1 year, the amount will be:

$$P + P \times r = P(1 + r)$$

Here, $P \times r$ is the earnest money from the capital P.

This amount, $P(1 + r)$, is the capital for the second year. After second year, the amount will be compounded to:

$$P(1 + r) + [P(1 + r) \times r] = P(1 + r)[1 + r] = P(1 + r)^2$$

Similarly, after 3 years, the amount will be compounded to $P(1 + r)^3$

Therefore, after N years, the amount will be: $P(1 + r)^N$

Let us express the compounded amount after N years (future value) by the symbol F.

Thus,

$$F = P(1 + r)^N \tag{12.17}$$

That is, we can say,

$$\text{Future value of any present amount} = (\text{Present amount}) \times (1 + \text{Rate of return})^N$$

where N is the number of years into the future that the income amount will be received.

Here, the factor $(1 + r)$ is termed as accumulation weight or compound factor.

Annual Compounding Rate for Multiple Payments

Assume an income stream where m is the number of payment per year. In this case, annual rate of return (r) can be split as r/m, and the present value can be computed as:

$$F = P\left(1 + \frac{r}{m}\right)^{Nm} \tag{12.18}$$

Single Installment Discounting

From the derivation of compounding present value (P) to a future value (F), one can have

$$F = P(1 + r)^N$$

Alternatively,

$$P = \frac{F}{(1 + r)^N} \tag{12.19}$$

Here, the factor $1/(1 + r)$ is termed as discounting weight *or* discount factor.

12.7.5.2 Uniform Annual Cash Flow

Accumulated Future Value: Compounding

Let us assume an irrigation project having a project period of N years where benefit (income) comes (or cost goes) in annual bursts, and the yearly amount is uniform throughout the project period, and it is denoted by A. We want to know the accumulated amount of benefit at the end of N years.

Here, the income from the project for the year N (last income) will not subject to compound because it will come at the end of the Nth year. Thus, the actual time period for compounding is (N− 1) year. The income of year 1, 2, 3, . . . (N− 1) will be compounded for year (N− 1), (N− 2), (N− 3), . . .1 year, respectively.

We know that compound amount from single income at the end of N years is $P(1 + r)^N$, where N is the number of years for which it is compounded.

In our present case, the income will be available at the end of each year. Thus, if we apply compound formula (from starting to ending of period) and add them to obtain the total future value, F, then:

$$F = A\left[(1 + r)^{N-1} + (1 + r)^{N-2} + \cdots + (1 + r)^2 + (1 + r) + 1 + 0\right]$$

Alternatively,

$$F = A\left[1 + (1 + r) + (1 + r)^2 + \cdots + (1 + r)^{N-1}\right] \tag{12.20}$$

Multiplying both sides of the above equation by $(1 + r)$, we obtain,

$$(1 + r)F = A\left[(1 + r) + (1 + r)^2 + (1 + r)^3 + \cdots + (1 + r)^N\right] \tag{12.21}$$

Subtracting (12.20) from (12.21) we get,

$$rF = A\left[(1 + r)^N - 1\right]$$

or

$$F = \frac{A[(1 + r)^N - 1}{r} \tag{12.22}$$

Annual Compounding Rate for Multiple Payments

Instead of yearly income, let us consider multiple income, m is the number of income per year. Here, the yearly compound rate can be considered for monthly as r/m. The resulting formula for monthly income series is:

$$F \times \left(\frac{r}{m}\right) = A_{\mathrm{m}}\left[\left(1 + \frac{r}{m}\right)^{Nm} - 1\right] \tag{12.23}$$

where A_{m} is the uniform monthly income.

Accumulated Present Value – Discounting

From the above equation, we obtain,

$$A = \frac{F \times r}{(1 + r)^N - 1} \tag{12.24}$$

12.7.5.3 Discrete Non-uniform Annual Cash Flow

In practical situation, the annual cost or benefit may not equal, and the cost or benefit may not exist in every year. For example, consider the case described below:

	Money comes or goes ($) for the year			
Year	1	2	3	4
Income	1,000	5,000	0	2,000
Cost	4,000	0	500	0

In such case, we have to find the net benefits for each year and then to convert them to future value or present value as needed (by compounding or discounting, respectively) with the single income formula, and then to sum up for total value.

12.7.6 Project Selection Among Alternatives

The best project alternatives may not be economically viable. We are interested in such a project that will yield a greater output for national economy. A test of viability needs to be applied to the alternative projects.

12.7.6.1 Indicators

The following indicators are used to compare the project alternatives:

1. Net present value (NPV).
2. Economic internal rate of return (IRR).
3. Benefit–cost ratio (BCR).

12.7.6.2 Comparative Merits and Demerits of Each Indicator

Both IRR and NPV are widely used to decide which investments to undertake and which investments not to undertake. The aim is to maximize the NPV, but notIRR. The major difference between IRR and NPV is that while NPV is expressed in monetary units (Dollar, for example), the IRR is the true interest rate expected from an investment expressed as a percentage.

The IRR is a rate or ratio, not an amount, thus more useful for comparing unlike investments. It is also useful for making comparisons between different sized farms and between different periods, and international comparisons. However, some IRR calculations require cash inflow as well as cash outflow.

The NPV is suitable for absolute measure of value of an inflow–outflow system. NPV is well accepted for sound reasons, but it has limitations. To solve for NPV, one must first calculate the opportunity cost of the capital, also called “discount rate.” The rate is used to calculate NPV. The NPV is highly sensitive to the discounting rate. Different discounting rates can change NPV ranking, and therefore not very useful for comparisons between organizations – specially those of different sized projects.

The BCR is a direct indicator of benefit (gain) or loss from a project. However, it does not tell us about the total income from the project alternatives; thus not suitable to compare different sized projects and mutually exclusive projects. At the same BCR (or even at lower BCR), the total income from a large project may be much higher than that of a small project.

In summary, it can be concluded that NPV and IRR give identical signal, and hence have essentially equivalent utility. The two measures complement each other. IRR is particularly suitable for comparing different sized projects. NPV is a better absolute measure, where IRR is a better relative measure. When a single indicator is used, the NPV and IRR can rank the alternatives differently. BCR, IRR, and NPV together can give a better picture of the problem than either alone.

12.7.6.3 Selection Criteria

Mutually Independent Projects

Independent projects are those projects which (any one) can be selected without any restriction on the others.

Essential criteria: (a) the BCR should be greater than unity and (b) the NPV should be positive.

Selection: Choose the project first having highest BCR and IRR. If fund is available, select sequentially all projects having BCR > 1 and NPV > 0. Select second project which have second highest BCR and IRR.

Mutually Exclusive Projects

Mutually exclusive projects are those projects from which any one can be selected with sacrificing of the others.

Essential criteria: (a) the BCR should be greater than unity and (b) the NPV should be positive.

Selection: Choose the project having higher NPV.

12.7.7 Examples on Financial Analysis and Project Selection

Example 12.2 Justify the proposal of lining of an existing earthen canal of a Deep Tubewell (DTW) irrigation scheme from the following information:
Discharge rate of the DTW = 2.5 cusec
Average daily operating hour during single crop period (4 months period) = 8
Overall water loss in the conveyance system = 40%
Tentative overall reduction of conveyance loss as a result of proposed main and secondary canal lining (10 km) = 20%
Cost of lining per km = 2,000 US$
Value (or cost) of water per cubic meter = 1.5 US$
Effective life of the lining = 12 years
Maintenance cost from fifth year at 3 year intervals = 300 US$ per km

Solution

Total cost of lining = $10 \times 2{,}000 = 20{,}000$ US$
Maintenance cost for 10 km at each time = $10 \times 300 = 3{,}000$ US$
Pump discharge, $Q = 2.5$ cusec $= 2.5 \times (2.83 \times 10 - 2) = 0.07075$ cusec (i.e., m^3/s)
Total flow during the crop period of the year $= 0.07075 \times (4 \times 30 \times 8 \times 3{,}600) = 244{,}512$ m^3
Reduction of water loss due to canal lining $= 244{,}512 \times 0.20 = 48{,}902$ m^3

Value of water saved as a result of lining (savings in revenue) = 48,902 × 1.5 = 73,353 US\$/year

Now, calculating the NPV in each year using the formula:

$$P = \frac{F}{(1 + r)^n}$$

Assuming IRR, $r = 10\% = 0.10$

For the year 5, the net income = cost − revenue = 73,354 − 3,000 = 70,354

The NPV for the year 5 = $70{,}354/(1 + 0.10)^5 = 43{,}684$ US\$

The NPV for other years can thus be calculated. The results are summarized below:

Year	0	1	2	3	4	5	6	7	8	9	10	11	12
Cost (\$)	200,000					3,000			3,000			3,000	
Revenue (\$)	0	73,354	73,354	73,354	73,354	73,354	73,354	73,354	73,354	73354	73,354	73,354	73,354
Net Income	−200,000	73,354	73,354	73,354	73,354	70,354	73,354	73,354	70,354	73354	73,354	70,354	73,354
NPV of net income	−200,000	66,685	60,623	55,112	50,101	43,684	41,406	37,642	32,820	31109	28,281	24,659	23,373
Sum of NPV of net income	295,495												

Since the NPV of the net income is positive, the project can be accepted.

Example 12.3. In a water-logged problem area, 100 ha land has the potential for crop production. The government wishes to set up a drainage system to regain the productivity of the land. As an engineer, you are asked to advise regarding the technical and economic feasibility of the proposed plan. From the study of the area, you are supplied with the following information:

Initial total cost of installation = 100,000 US\$

Yearly operational cost (collection and disposal of drainage outflow, maintenance, others, including salary of the technical staff) = 35,000 US\$

Effective life of the installed system = 15 years

Salves value at the end of the project = 10,000 US\$

Tentative yearly revenue to be generated from the sale value of the products = 50,000 US\$

Do you think that the drainage project is economically viable?

Solution

Initial cost =100,000 US\$

Effective life = 15 years

Operating cost per year = 35,000 US\$

Salvage value at the end of project (last year, i.e., 15th year) = 10,000 US\$

Net income at year 15 = revenue − cost = (50,000 + 10,000) − 35,000 = 25,000

Assuming IRR = 10%

NPV of net income at year 15 = $F/(1 + r)^n = 25{,}000/(1 + 0.10)^{15} = 5{,}985$

Similarly, NPV of net income of other years can be calculated in Excel. The results are summarized below.

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Cost ($)	100,000	35,000	35,000	35,000	35,000	35,000	35,000	35,000	35,000	35,000	35,000	35,000	35,000	35,000	35,000	35,000
Revenue ($)	0	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	60,000
Net Income	−100,000	15,000	15,000.0	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000	25,000
NPV of net income	−100,000	13,636	12,397	11,270	10,245	9,314	8,467	7,697	6,998	6,361	5,783	5,257	4,779	4,345	3,950	5985
Sum of NPV of income		16485.1														

The NPV of net income = 16,485.

Since the NPV is positive, the project is viable.

Example 12.4 A farmer has cash money of US$100,000. He has two options to invest it. He can save it in a bank from where he can get 10% interest per year. Another option is, he can hire (take lease) 100 ha agricultural land for 5 years by US $50,000 and cultivate the land investing the rest US$50,000for crop production. The expected outcomes (sale value of the products) from the agricultural field for the years are US$80,000, 100,000, 150,000, 100,000, and 85,000, respectively. The farmer seeks your consultancy to choose the best option. Which option will you suggest to the farmer?

Solution Option-1: Saving in Bank

Accumulated money from the bank after 5 years,

$$F = P(1 + r)^n = 100{,}000 \times (1 + 0.10)^5 = 161{,}051$$

Option-2: Taking lease of Agriculture Land

Discount rate = 0.10

Present value of the future amount,

$$P = \frac{F}{(1 + r)^n}$$

Using the relation, the NPV for different years are given below:

Year	0	1	2	3	4	5
Cost ($)	50,000	50,000	50,000	50,000	50,000	50,000
Revenue ($)	0	80,000	100,000	150,000	100,000	85,000
Income	−50,000	30,000	50,000	100,000	50,000	35,000
NPV	−50,000	27,273	41,322	75,131	34,151	21,732

Sum of NPV = 149,609
Future value (after 5 years) of the present amount, $F = P(1 + r)^n$
Taking compound rate equal to discount/interest rate, $F = 149{,}609 \times (1 + 0.10)$ 5 = 240,948

Thus, future value from land > future value from bank
Hence, taking lease of agricultural land is preferred.

Example 12.5 Perform economic and financial analysis of the 3 projects given below to justify the investment and suggest the best project option, if they are:

(a) Mutually independent.
(b) Mutually exclusive.

Assume, discount rate is 8%.

Project A

Year	0	1	2	3	4	5	6
Cost ($)	25,000	500	500	500	500	500	1,000
Revenue ($)	0	7,000	10,000	10,000	7,000	4,000	4,000

Salvage value at year 6 = 3,000 $

Project B

Year	0	1	3	5	7
Cost ($)	50,000	7,000	1,000	1,000	2,000
Revenue ($)	0	25,000	20,000	20,000	30,000

Project C

Year	0	1	2	3	5
Cost ($)	10,000	0	0	0	0
Revenue ($)	0	5,000	5,000	4,000	3,000

Solution NPV calculation:

Calculation sheet of DCF is given below. NPV for a particular year is calculated as:

$$\mathrm{NPV} = \frac{I}{(1 + r)^n}$$

where I is the income (i.e., revenue − cost), r is the discount rate, and n is the year.

Year	0	1	2	3	4	5	6
Cost ($)	25,000	500	500	500	500	500	1,000
Revenue ($)	0	7,000	10,000	10,000	7,000	4,000	7,000
Income	−25,000	6,500	9,500	9,500	6,500	3,500	6,000
NPV of income	−25,000	6,019	8,145	7,541	4,778	2,382	3,781
Sum of NPV	7,645						

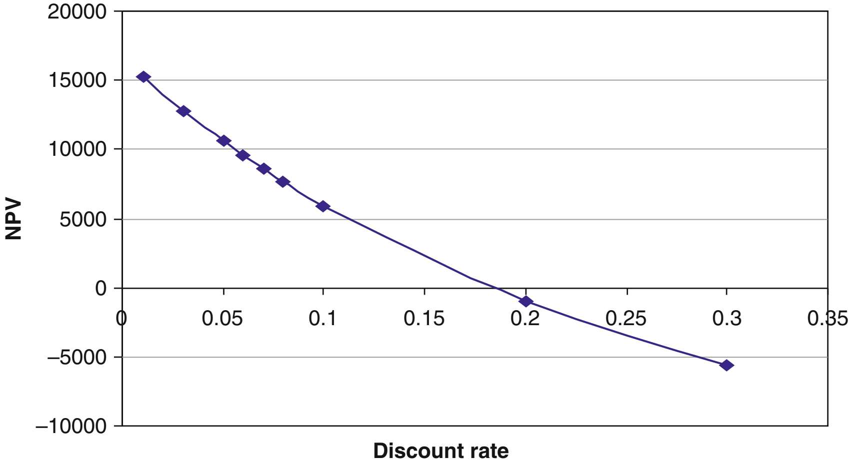
IRR calculation

For IRR calculation, the NPV at different discount rates are calculated. The results are given below:

Discount rate	0.01	0.03	0.05	0.06	0.07	0.08	0.1	0.2	0.3
NPV	15,198	12,778	10,581	9,557	8,580	7,645	5,897	−938	−5,593

Then the NPV is plotted against discount rate. From the graph, it is revealed that the NPV is zero at discount rate of about 0.19. Hence, the IRR is 0.19 or 19%.

BCR calculation



We know, BCR = revenue/cost

As the project is multiyear cash-flow system, the present value (PV) of the revenue and cost should be determined. The formula for determining PV of the cost is the same as that of NPV, as stated earlier. The summary of the calculation is given below:

Year	0	1	2	3	4	5	6
Cost ($)	25,000	500	500	500	500	500	1,000
Revenue ($)	0	7,000	10,000	10,000	7,000	4,000	7,000
PV of cost	25,000	463	429	397	368	340	630
PV of revenue	0	6,481	8,573	7,938	5,145	2,722	4,411

Sum of PV of cost (\$) = 27,627
Sum of PV of revenue (\$) = 35,272
Then, BCR = (35,272/27,627) = 1.28

Similarly, the NPV, IRR, and *B–C* ratio of the Project B and Project C are determined and summarized below:

	NPV (\$)	IRR (%)	BCR
Project A	7,645	18.4	1.28
Project B	11,018	13.8	1.19
Project C	4,133	26.4	1.41

12.7.7.1 Suggesting the Best Project

(a) *When the projects are independent*

All the projects produce NPV greater than zero and BCR greater than one. As the projects are independent, from the value of IRR and BCR, it is revealed that Project C generates the highest economic rate of return, thus it is the most economical. Thus, maximum possible number of projects like "Project C" should be materialized (upto which the prevailing condition permits). After that, if money is available, Project A should be established as it generates the second highest economic rate of return. Last of all, Project B may be considered.

(b) *When the projects are mutually exclusive*

Project B generates the highest NPV (hence the highest net return) among the projects, and Project A generates the second highest. So, Project B should be taken. If the available capital does not allow materializing Project B, then Project A should be taken. The last choice is Project C.

Example 12.6 A farm manager wants to deposit a certain amount of money with a target of having a total sum of 50,000 US\$ at the end of 10 years. If the bank interest rate is 8% (annually), find:

(a) What yearly deposit is required?
(b) What monthly deposit is required (instead of yearly)?
(c) What present deposit (one-time) is required instead of yearly or monthly deposit?
(d) What amount will be accumulated after 5 years with the yearly deposit scheme?
(e) What equivalent money (of five million at the end of 10 years) would be accumulated after 8 years?

Solution (a) For yearly deposit, we know, $F \times r = A_y[(1 + r)^n - 1]$

Here, $F = 50{,}000$ US\$, $r = 0.08$, $n = 10$ years, thus, $A_y = 1{,}852$ US\$ (*Ans.*)

(b) For monthly deposit, $F = A_{\mathrm{m}}\ [(1 + r/m)^{mn} - 1]/(r/m)$

Here, $F = 50{,}000$ US\$, $m = 12$, $n = 10$, $r = 0.8$
Thus, from the above equation, $A_{\mathrm{m}} = 273$ (*Ans.*)

(c) $F = P(1 + r)^n$ or $P = F/P(1 + r)^n$

Here, $F = 50{,}000$, $n = 10$, $r = 0.08$, thus $P = 23{,}160$ US\$ (*Ans.*)

(d) Amount after 5 years $F = A_{\mathrm{y}}[(1 + r)^n - 1]/r = 1{,}852 \times \{(1 + 0.08)^5 - 1\}/0.08$

Thus, $F = 33{,}998$ US\$ (*Ans.*)

Example 12.7 An agro-farm manager took a loan of 50,000 US\$ from the bank with an interest rate of 10%. He is able to repay by 1,000 \$ per year. Find the number of payments (i.e., no. of year) required to repay the loan.

Solution Let the number of years required = n.
At year n, the value of present loan is $F = P(1 + r)^n$
Annual payment = 1,000 US\$
After each year (from year 1), the value of loan money, payment, and the residual is summarized below (as trial and error method) using Excel spreadsheet tool. Here, residual after year 1 is the capital for the second year (for interest calculation).

n	F (loan)	A	Residual
1	55,000	10,000	45,000
2	49,500	10,000	39,500
3	43,450	10,000	33,450
4	36,795	10,000	26,795
5	29,474.5	10,000	19,474.5
6	21,422.0	10,000	11,422.0
7	12,564.1	10,000	2,564.1
8	2,820.6	10,000	−7,179.4

Hence, at the end of the eighth year, the payment needed is 2,820.6 US\$.

Example 12.8 A bankers' group offers a plan in which a yearly deposit of \$1,000 for 20 years will provide a total return of \$50,000. What is the interest rate (rate of return) the group offers?

Solution For yearly deposit, we know, $F \times r = A_{\mathrm{y}}[(1 + r)^n - 1]$
From the above equation,

$$\log_{10}\left(\frac{rF}{A_{\mathrm{y}}}\right) = n\log_{10}(1 + r) - \log_{10} 1 \qquad (12.25)$$

Here, $A = 1{,}000$ \$, $n = 20$ years, and $F = 50{,}000$ \$.

Assuming trial value of r and comparing the both sides of (12.25):

r	LHS	RHS	Difference
0.08	0.60206	0.668475	−0.06642
0.09	0.653213	0.74853	−0.09532
0.1	0.69897	0.827854	−0.12888
0.11	0.740363	0.90646	−0.1661
0.085	0.628389	0.708595	−0.08021
0.0795	0.599337	0.664453	−0.06512
0.07	0.544068	0.587676	−0.04361
0.065	0.511883	0.546992	−0.03511
0.064	0.50515	0.538833	−0.03368
0.06	0.477121	0.506117	−0.029
0.055	0.439333	0.465049	−0.02572
0.05	0.39794	0.423786	−0.02585
0.0555	0.443263	0.469165	−0.0259
0.056	0.447158	0.473278	−0.02612
0.057	0.454845	0.4815	−0.02665
0.0558	0.445604	0.471633	−0.02603

Minimum difference between LHS and RHS is at $r = 0.055$

Thus, $r = 0.055$ (*Ans.*)

Example 12.9 In order to save $1 million in 20 years (to retire), assuming an annual return (interest) of 12.2%, find out how much you need to invest each month to achieve your goal?

Solution For uniform annual compounding of multiple payment, we have, $F \times (r/m) = A_{\mathrm{m}}\,[(1 + r/m)^{mn} - 1]$

Here, $F = 100{,}000$ \$, $m = 12$, $n = 20$, $r = 0.122$

Thus, from the above equation, $A_m = 983.94$ \$ (*Ans.*)

Relevant Journals

- Journal of Economic Theory
- Agricultural Economics
- Environmental and Resource Economics
- Journal of Financial Economics
- Journal of Economics and Business
- Journal of Empirical Finance
- Agricultural Water Management
- Journal of ASCE
- Irrigation Science
- Journal of ASAE

Questions

1. Describe the importance of economic considerations in irrigation management.
2. Do you think that water is an economic good? Why is economic analysis important in water allocation planning?
3. Narrate the characteristics and behaviors of cost and revenue curve.
4. What is opportunity cost? What are the possible options for optimizing water level?
5. Narrate the mathematical norms for maximizing net benefit.
6. What are the categories and components of cost of production? Differentiate between partial budget and full budget analysis.
7. What are the importance of economic and financial analysis in developing irrigation projects?
8. Write short notes on: NPV, NFV, BCR, cost effectiveness, least-cost analysis.
9. What are the steps in NPV analysis? What is NPV curve?
10. What are the economic indicators used to compare the project alternatives? Describe their merits and demerits.
11. Narrate the selection criteria for: (a) mutually independent, and (b) mutually exclusive projects.
12. Perform economic and financial analysis of the given projects to justify the investment, and suggest the best project option, when they are: (a) mutually independent, and (b) mutually exclusive. Assume a discount rate of 10%.

Project A

Year	0	1	2	3	4	5
Cost ($)	50,000	5,000	5,000	5,000	5,000	5,000
Revenue ($)	0	10,000	40,000	40,000	30,000	20,000

Project B

	Year				
	0	1	2	4	6
Cost ($)	50,000	7,000	1,000	1,000	2,000
Revenue ($)	0	25,000	50,000	30,000	25,000

Project C

Year	0	1	2	3
Cost ($)	100,000	5,000	5,000	5,000
Revenue ($)	0	80,000	70,000	60,000

13. From a field investigation of irrigation management strategies in wheat production, the following information is available:

Frequency of irrigation used	Total water applied (cm)	Grain yield (t/ha)	Straw yield (t/ha)
4	30	5.70	7.00
3	20	5.40	6.60
2	12	4.40	6.10
1	6	3.03	6.29
0 (non-irrigated)	0	1.70	3.90

Market price of wheat: 160 S$/t
Market price of straw: 10 $/t
Cost per irrigation: 32 $/ha
Land use cost (rent of land for 6 months): 150/ha
Power tiller cost (for land preparation): 50 $/ha
Cost of fertilizer: 52 $/ha
Cost of seed: 30 $/ha
Cost of insecticide: 10 $/ha

Human labor requirement (per hectare):
  Land cleaning – 8 nos
  Sowing (manual) – 2 nos
  Weeding and thinning – 36 nos
  Insecticide spray – 2 nos

Harvesting, carrying:
Irrigated plots – 22 nos
Non-irrigated plot – 15 nos

Threshing, cleaning:
Irrigated plots – 37 nos
Non-irrigated plot – 25 nos
Cost of human labor (per person per day): 5 $
Interest rate: 10%

Perform:

(a) Partial budget analysis under both land- and water-limiting conditions.
(b) Full budget analysis under both land- and water-limiting conditions.
(c) Propose best irrigation management option.

14. A low-land has the potential for crop production but problem of water-logging. The local authority wishes to establish a drainage project to regain the productivity of the low-land. As an engineer, you are asked to study the economic feasibility of the proposed project. For the area, the following information are available:
Total area = 170 ha
Initial total cost of installation = US$110,000
Yearly operational cost (collection and disposal of drainage outflow, maintenance, others, including salary of the technical staff) = US$30,000
Effective life of the installed system = 14 years
Salves value at the end of the project = US$12,000
Tentative yearly revenue to be generated from the sale value of the products = US$55,000
Bank interest rate for that area = 10%.

15. Justify the proposal of lining of an existing earthen canal of a Deep Tubewell (DTW) irrigation scheme from the following information:
Discharge rate of the DTW = 2.2 cusec
Average daily operating hour during single crop period (5 months period) = 10
Overall water loss in the conveyance system = 45%
Tentative overall reduction of conveyance loss as a result of proposed main and secondary canal lining (9 km) = 25%
Cost of lining per kilometer = US$2,200
Value (or cost) of water per cubic meter = US$2.0
Effective life of the lining = 15 years
Maintenance cost from fourth year of construction at 2 years interval = US $250 per km
Assume standard value of any missing data.

References

English M (1990) Deficit irrigation. I. Analytical framework. J Irrig Drain Eng 116(3):399–412

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