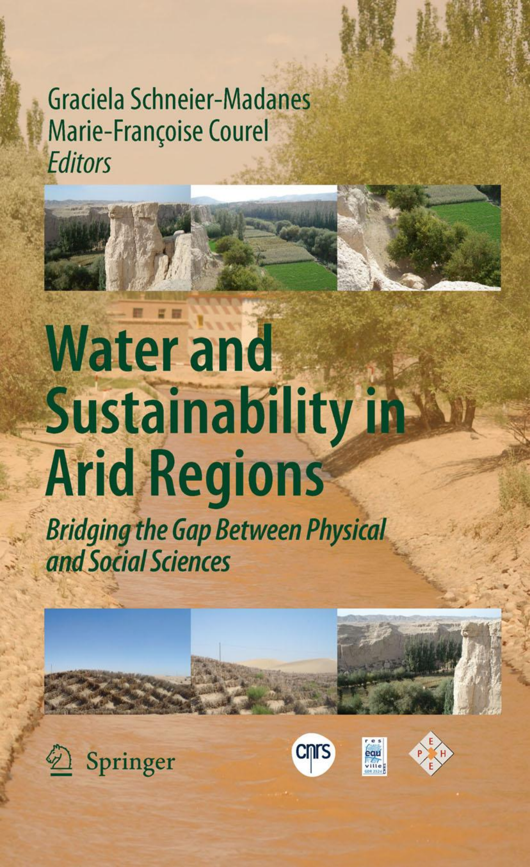
Graciela Schneier-Madanes
Marie-Françoise Courel
Editors



Water and Sustainability in Arid Regions

Bridging the Gap Between Physical and Social Sciences

Springer

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ISBN 978-90-481-2775-7 e-ISBN 978-90-481-2776-4
DOI 10.1007/978-90-481-2776-4
Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2009927005

Printed on acid-free paper

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

Preface

> *The Sahara, Kalahari, Namib, Sinai, Karakum, Taklimakan, Gobi, Sonoran, Great Basin, Mojave, Colorado, Atacama . . .*
>
> *Our ideas of such extreme arid regions often are influenced by the media: photographs of vast "mineral universes" and powerful images of infinite horizons, frightening silences, wind-blown sand, nomads, and dead valleys. The most modern imaging techniques, including remote sensing and GIS, dissimulate the diversity of these spaces and their present and past plant, animal, and human life. Occasionally, archaeological discoveries remind us of the historical insight these allegedly empty spaces can provide. These vestiges of human habitation remind us that water is—or was—there, somewhere.*
>
> *The desert, and in general the "arid world," has assumed a mystical quality in contemporary societies, which tend to think of it a vast field of the absolute, infinity, reflection, a symbolic framework, or a "soul's mirror" that starts with a vision or perception of space and carries us along a philosophical voyage. The desert also represents emptiness: don't we talk about the political, cultural, and artistic "desert"? This image of desert as a void dates back to antiquity: as far back as the fifth century B.C., Herodotus recalled an army that "disappears in the desert."*
>
> *Literally or figuratively, the different meanings of desert continued to expand as scientists began to better grasp the workings of these arid lands. Merchants, travelers, explorers, entrepreneurs, and researchers continue to invest in deserts with hopes of unlocking their secrets. During the twentieth century, some isolated arid regions progressively became accessible to scientific missions whose goals included discovering how humans adapted to the harsh environment and how they survived. The management of water is the key to answering these questions and understanding the arid world.*
>
> *Current environmental crises and their worldwide social impacts fully justify the topic presented during this cycle of international conferences, which will convene physical, natural, human, and social scientists to provide an overview of contemporary water issues in arid regions from an interdisciplinary perspective . . .*

These were the opening words for the 1st WATARID International Conference, "Water, ecosystems and sustainable development in arid and semi-arid areas," which was held at the University of Xinjiang, China, on October 9–15, 2006.[1]

Two hundred-fifty scientists attended, representing more than 40 countries including China, France, Germany, Spain, Iran, Russia, Croatia, Uzbekistan, Tadjikistan, Japan, India, Morocco, Tunisia, Egypt, the United States, Argentina, Brazil, and Peru. The conference[2] was part of a scientific partnership between the

Ecole Pratique des Hautes Etudes (France), the University of Xinjiang (China), and the University of Teheran (Iran).

The three scientific institutions organized the event around a central concept: only an interdisciplinary approach to water as a scientific object, that is, a complex system driven by both natural and social sciences, can articulate different scales and interactions of water in arid and semiarid regions. It was from that hypothesis that this book was born.

The main objectives of the conference were to inventory water resources in arid and semiarid zones, offer an overview of the evolution of agricultural techniques and practices, and produce a historical, empirical, and theoretical analysis of the relationship between humans and water. To accomplish these goals, the conference was organized into four workshops:

(1) Water and the Environment was aimed at cataloging water resources in arid and semiarid regions and discussing the effects of climate change on these resources, salinization, modeling, and other topics.
(2) Water and Agriculture presented an overview of agricultural techniques and practices. Many contributions and debates developed around the concept of virtual water and exploitation of aquifers by agriculture.
(3) Water and Civilization included discussions on water and the State; architecture, cities, and hydraulic infrastructure; water economy traditions; cultural practices; and water law.
(4) Issues and Perspectives for the Future encompassed globalization and international actors, development issues, and new management systems and environmental constraints.

Support for the conference came from several scientific organizations, namely Centre National de la Recherche Scientifique (CNRS) Départment Sciences Humaines et Sociales and Institut National des Sciences de l'Univers (INSU); the CNRS Urban Water Research Network "res-EAU-ville," which organized the conference with Ecole Pratique des Hautes Etudes (EPHE) and the University of Xinjiang; and CNRS/PRODIG/Université Paris 1 Sorbonne. Associations and enterprise partners included Veolia Water, Iranian Water, and the International Water History Association.

Notes

1. Professor Marie-Françoise Courel, president of the conference. Graciela Schneier-Madanes is the scientific contact for the conference. Conference information can be found at http://www2.ephe.sorbonne.fr/ watarid/en/index.html.
2. "Water, ecosystems and sustainable development in arid and semi-arid areas," 1st WATARID International Conference, CD-ROM, 2008.

Acknowledgments

The editors would like to express their gratitude to the contributing authors for their dedication to this project. We hope they found the experience to be worthwhile and the final product to be a valuable resource for further research and international networking.

This book is the result of transcontinental and trans-Atlantic teamwork. The authors especially wish to thank Stephanie Doster, Laura María Díaz Villalba, and Margaret Deignan, who made this book come to life.

In the U.S., Stephanie Doster, an associate editor at the University of Arizona and a former newspaper reporter who has lived around the world, was the most creative and professional assistant editor we could have asked for. Her commitment to this project was instrumental in navigating the complexities of an international collaboration and understanding the scientific and global culture inherent to the book.

In France, Laura María Díaz Villalba, research and publications assistant of the "res-EAU-ville" Centre National de la Recherche Scientifique (CNRS) research network, exhibited her international background and management skills. As the liaison between editors, authors, peer reviewers, and the publisher, she proved invaluable at monitoring the book's progress and keeping the editing process moving in a seamless and timely manner.

Margaret Deignan, associate editor, Environmental Sciences Unit at Springer in Dordrecht (The Netherlands), enthusiastically embraced the idea of the book and worked closely and patiently with us to complete the project. We also would like to express our appreciation to her helpful staff.

We gratefully recognize Barbara Morehouse, deputy director for research, Institute of the Environment at the University of Arizona (USA), and Professors Ghislain De Marsily, French Academy of Sciences, and Tashpolat Tiyip, University of Xinjiang, China, for their important contributions to the project from the outset. We also would like to acknowledge Sam Drake at the University of Arizona for his scientific assistance in preparing the book.

Finally, we wish to extend our thanks to the peer reviewers for generously giving their time and for their constructive suggestions and expert evaluations.

Peer reviewers from France included Anne Coudrain, Institut de Recherche pour le Développement (IRD), Montpellier, France; Olivier Grunberger, IRD, Montpellier, France; Michel Meybeck, Université Paris VI; and François Molle, IRD, France.

In the US, peer reviewers were Michael Bonine, Laura Lopez-Hoffman, Stuart Marsh, Christopher Scott, Terry Sprouse, and Margaret Wilder, all of the University of Arizona; the late Marvin Cohen, attorney, Arizona; and Soroosh Sorooshian, University of California-Irvine.

Rounding out the international group of peer reviewers were Pedro Berliner, Ben-Gurion University of the Negev, Israel; Fekri Hassan, University College London; Victor Pôchat, University of Litoral, Argentina; Garry Willgoose, University of Newcastle, Australia; and Claudio Zucca, University of Sassari, Italy.

We are also grateful for the advice of David C. Goodrich, USDA-ARS, Southwest Watershed Research Center in Tucson, Arizona. Invaluable contributions also came from Michelle Ducousso, of CNRS/PRODIG, who provided assistance with graphics, and Michael Lavin, of the United Kingdom, whose French/English translations were essential to a number of chapters in the book.

The photographs on the book cover were taken by Marie-Françoise Courel during 2007–08 field research.

Last but not least, the book would not have been possible without support from the CNRS Institute for Humanities and Social Sciences (INSHS), Institute of Ecology and Environment (INEE), and “res-EAU-ville.” Finally, important help also came from Unité Mixte Internationale/Joint International Center on Water, Environment and Public Policy, CNRS/University of Arizona.

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Introduction

In arid regions, water resources and their use and preservation pose major challenges. Our current model of development, with extensive agriculture, accelerated urbanization and poverty, and increasing pollution has created tensions and questions about future access to water. Understanding these issues in a global context and in terms of sustainable development requires combining findings from observations of and data from physical processes and social practices at different temporal and spatial scales.

This type of interdisciplinary approach can be particularly valuable in tackling questions in arid lands,[1] where natural phenomena and human societies are so intricately connected, and often have been for millennia. The environmental and ecological issues facing arid lands, such as water scarcity, salinization, desertification, etc., are not one-dimensional; rather, it is through interdisciplinary, multilayered research that biophysical and social scientists, working together, can effectively assess and address the complexity of the issues.

This book is a step toward addressing interdisciplinarity through dialogues between disciplines and academic traditions. It is a compilation of international research that illuminates different facets of water and sustainability in arid lands through varied and comparative perspectives and methods. The idea is that by grouping together an array of research that is seldom presented together (hydrology, ecology, remote sensing, archaeology, geography, architecture, economy, and political science), a common language—a common set of global concepts—will gradually emerge that contributes to international dialogue on some of the world's most pressing issues and reinforces the role of science as an environmental steward.

The research presented here encompasses many of the Earth's arid and semiarid regions: Xinjiang province in northwestern China; Iran; a significant portion of the arid Mediterranean, including the Maghreb and southern Europe; and parts of North, Central, and South America. A strong corps of peer reviewers from around the world reflects the book's global scale and is testimony to the active current international debate and scientific research on the subject of water in arid lands. With the exception of Part II, which offers a historical perspective to help better understand today's water issues, the body of work contained in the book focuses on research that is mostly related to the "sustainability era" beginning in the 1990s.

With this in mind, the book is organized into three parts: Contemporary Issues, Learning from History, and Management for Sustainability.

Contemporary Issues presents an overview of interactions between water resources and aridity and analyzes emblematic subjects and methodologies, including salinization, oasis[2] environments, and remote sensing. This section does not aim to present a comprehensive look at research fields related to water in arid lands. Instead, it offers a selection of case studies and techniques, progressing from local to national and from regional to international scales. From these topics emerge new challenges, such as food security, climate change, and biodiversity.

Lessons from History aims to improve understanding of arid societies through analysis of their technical and sociocultural systems. Focusing on built heritage as it pertains to infrastructure, such as qanat systems, and architecture in oasis towns, the chapters detail how human ingenuity since ancient times has transformed hostile environments into habitable areas. The legacy of these practices raises critical questions about sustainable development and the way we think about solutions to water scarcity problems: What role does (or could) traditional technology and infrastructure play in achieving a more comprehensive, more appropriate, and more environmentally and socially concerned future water management policy?

Management for Sustainability explores court battles over water, arsenic contamination, rapid urbanization, forest restoration, and other case studies through discussion of governance and current experiences and practices. Sustainable development is considered here as a heuristic methodology, providing different insights into geopolitics, economics, and emerging water management issues. Framed by a global overview of water resources in arid regions and a historical perspective spanning 50 years of water resources management, this section presents strategies to improve management of available resources through adaptation to the specific conditions of each area.

The chapters in this book approach the question of sustainability by illuminating specific principles, lessons, and research methods. The authors employ an array of descriptive, analytical, and narrative styles, such as field research notes. A few of the chapters, geared toward a more general audience, provide a context and foundation for other discussions in the book. Despite exploring different topics and methodologies, the chapters are intertwined in a unique architecture that adds to the cohesion of the book. Relevant research in one chapter is referenced in another, lending more depth to the work presented.

Part I

The seven chapters that make up this section on *Contemporary Issues* highlight the complex interactions between water resources, the environment, and human actions in three main arid regions: northwestern China, Iran, and the Maghreb. Occurring particularly in arid and semiarid regions, soil salinization is the most common land desertification and land degradation process. The first four chapters examine this problem in the arid northwestern region of China through three detailed case studies focused on the Xinjiang Uygur Autonomous Region. Zheng and Yin (Chapter 1) open the book with a discussion on the importance of understanding the complexity of land degradation, an analysis of eco-reconstruction, and a call for more coordinated management and more respect for nature. Tiyip et al., (Chapter 2), LV et al., (Chapter 3), and Tashi et al., (Chapter 4) illustrate the value of remote sensing techniques in enhancing our understanding of those processes in a region where little remote sensing research has been carried out: the oasis of Keriya in the southern part of the Taklimakan Desert.[3]

This section also presents extensive national and regional case studies on water resources and related implications for development in Iran and the Maghreb (Tunisia, Algeria, Libya, and Morocco). The case study of Tunisia is particularly detailed. Common across these chapters are concerns about water scarcity and its relation to agriculture-surface water-groundwater interactions in the context of growing economic demand and urbanization.

Zehtabian, Khosravi, and Ghodsi (Chapter 5) and Djellouli-Tabet (Chapter 6) analyze spatial and temporal patterns of national or shared water availability and current problems such as the decline of soil and water quality, salinization, land degradation, and desertification. The authors present an overview of strategies—a “big hydraulic approach”—for coping with these issues, from water transfers to seawater desalination, and call for the use of new concepts like territorial and social equity and nonconventional solutions.

Through a thoroughly analyzed case study on Tunisia, Besbes et al. (Chapter 7) conclude the section by reshaping the question of water scarcity in arid lands. The authors discuss new research problems connected to the field: consequences of climate change, biodiversity, and national food security. Exploring these concepts, the chapter also delves into the potential competition between food production and bioenergy production at a global level.

Part II

Lessons from History examines arid societies and environments, through the concept of built heritage, in terms of man’s footprint on the landscape and as an approach to sustainable water management. Built heritage (within “Tangible Cultural Heritage”)[4] refers to the legacy of physical artifacts inherited by a group. It includes objects significant to the archaeology, architecture, science, or technology of a specific culture (buildings, historic places, monuments, etc.) that are considered worthy of preservation for the future. This notion was extended to include natural resources, biodiversity, and environment as “natural heritage” under the 1972 UNESCO Convention Concerning the Protection of World Cultural and Natural Heritage. The notion implies the necessity of preservation by the current generation for future generations.

Emblematic built heritage in arid regions includes water infrastructure and technology, such as the qanat, and architecture of oasis towns. Adapted to arid zones, the qanat is an ancient system of tunnels that conveys water for hundreds of kilometers for irrigation, domestic use, and energy. Also known as a karez, khettara, foggara, and other names, the system has been used in many countries throughout the world. The number of fully or partially functional qanats remains unknown; data vary due to lack of information, collapse, and abandonment of the systems.

The idea of preserving and revitalizing such a system without destroying it has emerged as an important aspect of historical and architectural research and urban planning. Synchronized to climatic conditions, the qanat protects the groundwater balance and appears to be more resilient than wells but unable to deliver the amount of water required for modern agriculture. A qanat is not only a technical system but also a social and cultural one, with patterns of solidarity, hierarchy, and power; the building, maintenance, and use of qanats is regulated primarily at local levels, which can lead to power struggles with highly centralized governance systems.

Case studies from three countries—Iran, China, and Morocco—address this critical question: In our scientific and technical world, where water technology has developed based on a model of big infrastructure, water transfers, and inexhaustibility of the resource, does a place still exist for traditional technology in modern water management?

Ahmadi et al. (Chapter 8) and El Faiz and Ruf (Chapter 10) illustrate the main characteristics and issues surrounding the systems in different contexts (Iran and Morocco) while providing a foundation for understanding and reconsidering the use of this technology on global and local scales. With many systems being abandoned in this era of modernization and urbanization, Sors' award-winning architectural project illustrates the possibilities for revitalizing foggara systems in Marrakech and for integrating them into urban development. Kobori (Chapter 9), meanwhile, takes a different approach, discussing the early days of karez research, beginning in the 1980s in Turpan (Xinjiang), and the reasons for the system's decline. Florenzano et al. (Chapter 11) build on the idea of urbanization with a discussion of the ancient city of Kashgar (Kashi) and its endangered built heritage, which developed around a central water supply. Digital conservation is helping to preserve the architecture of this oasis town, which sits at the intersection of Silk Road caravan routes in the Taklimakan Desert. Finally, Debaine-Francfort et al. (Chapter 12) use comprehensive archaeological findings and data to illustrate the fragility of the oasis environment of the Taklimakan Desert and how the desert has changed in response to human habitation. Interesting connections can be established between this chapter and the one by Tashi et al.

Part III

Water management is a complex endeavor that has evolved in recent years in terms of paradigms and approaches, such as reconstruction and restoration. The seven chapters in this section have a common denominator—governance—which is presented from different angles and through examples. Authorship in most of these case studies combines disciplines: hydrologists analyze the tendency of regulations to flout hydrological sciences; economists and climate scientists analyze climate forecasts; chemists interact with health managers; ecologists collaborate with remote sensing specialists; and public policy and arid lands experts weigh in on changing models of water management in arid lands.

Using three categories of renewable resources, Margat (Chapter 13) discusses an original geopolitical approach for water resources management in arid and semiarid regions and forecasts consequences of development for different countries. Readers will find interesting connections with several other chapters (e.g., Chapters 5–8, 10).

Calling for conjunctive management of surface water and groundwater, Valdes and Maddock (Chapter 14) analyze the current situation in the US Southwest. Growing population and climate variability have fueled water demand, leading to unsustainable use. In their discussion, the authors explore the disconnect between laws regulating water pumping and scientific principles of hydrology. A series of examples are presented to illustrate some of the successes and failures of integrated surface water and groundwater management and related legal implications.

Moving south to Argentina, Gimenez et al. (Chapter 16) present an alternative method for forecasting streamflows, in a river basin with arid characteristics, as a tool for making better decisions in irrigation management. Pineda-Pablos and Salazar-Adams (Chapter 15) provide a framework for understanding an issue of critical importance—urban growth and water scarcity—using the northern Mexico borderlands as a case study. While presenting the interrelated processes of growth, climate change, and urban water management, the authors show that current and future urban water crises are determined more by human and social actions than by natural factors.

Shifting back to South America, Pérez-Carrera and Fernandez Cirelli (Chapter 17) provide an overview of arsenic contamination in surface water and groundwater in Argentina and Chile—two areas known to be among the most affected in the world. The discussion forms the basis for defining different strategies to achieve sustainable management of the available drinking water resources, adapted to the specific conditions of each area.

Within the conceptual framework of sustainability, evaluating and disseminating results of management actions have become an essential tool to preserve ecosystem services. Bautista et al. (Chapter 18) examine a recent integrated project: monitoring and evaluating 40 historic forest restoration sites across the northern Mediterranean. The collaboration between researchers, managers, and decision makers makes this interdisciplinary approach effective and sustainable.

Last but not least, Hutchinson et al. (Chapter 19) explore how arid lands have been a testing ground for ideas on water management. The authors present a historical summary to explain how a technically oriented, top-down, and state-controlled management approach has evolved over half a century into a more comprehensive, regional, and local practice. The integrated water management vision/paradigm testifies to the globalization of water governance.

In summary, this book aims to offer an innovative exploration of critical issues of water in arid regions by bringing together an international and interdisciplinary body of authors who do not usually work together. By presenting and combining observations and data at different scales from both the physical and social sciences, we hope the book makes a valuable contribution to interdisciplinary research and the question of water resources and sustainability.

Notes

1. Editor's Note: Readers will find that some chapters use the terms arid lands and drylands interchangeably. But, in general, the book adheres to the definition of drylands given by the Smithsonian Institution and UNEP: "Drylands include arid, semi-arid, and dry sub-humid areas all over the world . . . Almost 40% of the Earth's total land surface is dryland. These areas are defined by their modest water supply; less than that found in the world's forest regions, yet greater than that of the deserts. Drylands go by many names: plains, grasslands, savannas, steppes or pampas. The Earth's hyper-arid areas, which include the great deserts, are not considered part of the drylands."
2. Following geologist Philippe Chamard, an oasis is a site where sedentary nomads have taken advantage of the presence of water to create an artificial ecosystem for agriculture, trade, and civilization. An oasis serves as a harbor where caravans and nomadic groups can rest and replenish supplies.
3. Considered the paradigm of cold deserts.

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Part I
Contemporary Issues

Chapter 1
Eco-reconstruction in Northwest China

Du Zheng and Yunhe Yin

Abstract The northwest arid region of China has a long history of economic development. With the emergence of environmental and sustainability concerns in recent years, more attention has been paid to the strategy of developing this region, raising issues of land degradation, the use of water and land resources, and eco-reconstruction. Understanding the complex interactions between land, vegetation, and degradation is necessary to build policies for eco-reconstruction and sustainable water use. Land degradation in arid and semiarid regions is dominated by sandy desertification caused by wind erosion, secondary salinization of soil due to poor drainage and intensified evapotranspiration, and degradation of rangeland by excessive cultivation and overgrazing. This situation intensifies the conflict among humans for land and resources and has serious social, economic, and ecological consequences.

Keywords Eco-reconstruction · Land degradation · Water resources · Northwest China

1.1 Aridity in the Northwest Region of China

The northwest arid region of China is characterized by little precipitation and high potential evapotranspiration. Climatic indices such as the aridity index, the ratio of potential evapotranspiration to precipitation, are used to quantify natural regional differences in moisture conditions.[1] In addition to climate, physical factors such as vegetation and soil provide the main scientific basis for the delineation of arid or humid regions. An aridity index of less than 1.0 indicates the humid zone, an index of about 1.5 delineates the subhumid and semiarid zone, and more than 3.5 defines the arid zone (Huang 1989).

In a broad sense, the arid northwest region of China includes semiarid rangeland in eastern Inner Mongolia and arid desert areas in western Inner Mongolia, Ningxia,

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G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
DOI 10.1007/978-90-481-2776-4_1,

Fig. 1.1 Northwest arid region of China

Gansu, and Xinjiang provinces[2] (Fig. 1.1). The essential physio-geographical features were described by Huang (2003a) as follows:

Arid zone: Precipitation is much less than potential evapotranspiration. Natural vegetation is mainly semi-desert or desert scrub, and soil generally takes on a limy character with little organic material or mineral nutrients. Salinization is rapid in areas of poor drainage. Crops generally cannot be cultivated without irrigation, except in some mountainous regions with good moisture conditions. Crop production is even more variable than in the semiarid zone due to fluctuating annual precipitation.

Semiarid zone: Precipitation is less than potential evapotranspiration. Natural vegetation is mainly grass, a calcium deposit layer in the soil is common, and soil organic matter and mineral nutrient content is low. Salinization is prone to occur in areas with poor drainage. Crops can be cultivated even without irrigation, but with variable yield. Without conservation measures, wind erosion can decrease soil fertility. Drought often occurs because of significant fluctuation in annual precipitation. Shrubs or trees could be grown in certain high-altitude mountainous regions, shaded canyons, or areas with favorable moisture conditions.

It is essential to understand these regional differences in moisture conditions. Countermeasures to deal with land degradation and eco-reconstruction interventions could be set up according to the particular physio-geographical features in different areas, providing a scientific macro-framework for land planning and water resources development.

1.2 Complexities of Natural Processes

Land degradation can be defined as the process and result of diminishing soil quality and its potential productivity through imprudent land utilization and adverse changes, such as global warming. Land degradation in arid and semiarid regions is dominated by sandy desertification caused by wind erosion, secondary salinization of soil due to poor drainage and intensified evapotranspiration, and degradation of rangeland by excessive cultivation and overgrazing. Land degradation, which restricts sustainable production and living standards, intensifies the conflict among humans for land and food and has severe social, economic, and ecological consequences.

1.2.1 Sandy Desertification

Sandy desertification, mainly caused by imprudent human activities in vulnerable arid or semiarid environments, is the most prominent environmental issue in the northwest arid region. This type of desertification includes four main processes: mobilization of sand dunes, desertification of grass steppe, coarsening of soil by wind erosion, and formation of badlands. Sandy desertification is distributed in patches in the eastern semiarid rangeland of the region and at the edge of desert oases in the western arid areas (Wang 2003) (see Chapters 3 and 4).

Sandy desertification has covered 103×10^3 km^2 and 218×10^3 km^2 in the arid and semiarid areas of the region, respectively, constituting 27.8% and 58.8% of all land suffering from sandy desertification in northwest China (Fig. 1.2) (Wang and Dong 2002). In comparison, in 2000, 385.7×10^3 km^2 of sandy desertification covered northern China—both the northwest and northeast regions of the country—of which 139.5×10^3 km^2 (36.1%) was lightly desertified, 99.8×10^3 km^2 (25.9%) was moderately desertified, 79.1×10^3 km^2 (20.5%) was heavily desertified, and

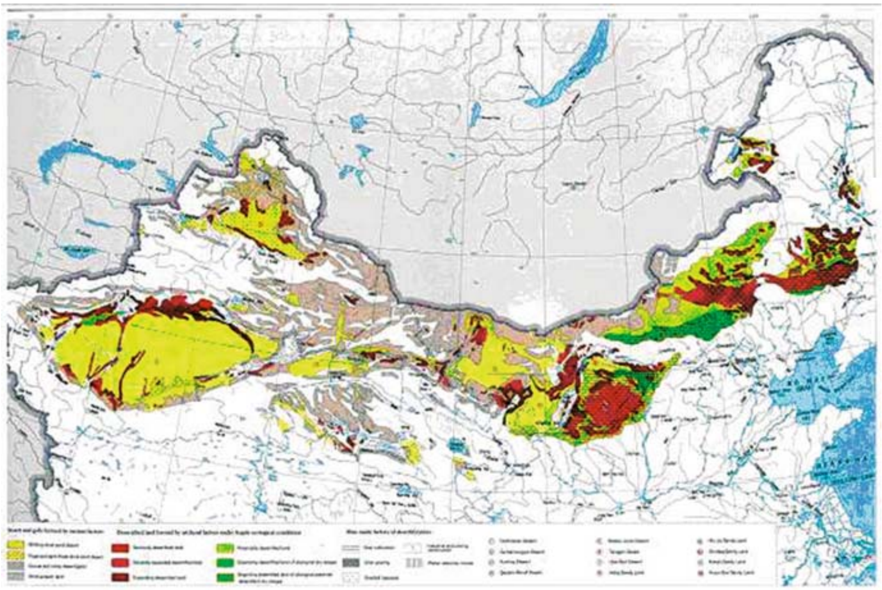

Fig. 1.2 Land desertification in northern China

67.5×10^3 km^2 (17.5%) was severely desertified. Compared with monitoring results from 1980, the figures show that the area of light desertification decreased, the area of moderate desertification was stable, and the heavily desertified area increased (Wang 2003), which was in agreement with desertification evolution trends and the strategy of implementing easy control measures first and then difficult ones.

1.2.2 Secondary Salinization

In arid and semiarid regions, a high ratio of evaporation to precipitation and high mineral concentrations in groundwater have caused secondary salinization, which is characterized by upward movement of soil water by capillary action and evaporation and salt accumulation at the surface. Irrigation without periodic leaching and drainage also can induce secondary salinization by dissolving salts accumulated in surface soil.

Among China's main provinces,[3] secondary salinization is most severe in the Xinjiang Autonomous Region, where 1.26×10^6 hectares (ha)—30.58% of the total farmland—is affected. Inner Mongolia ranks second with 1.80×10^6 ha (23.8% of its arable land) affected (Wang and Dong 2002). In Hetao, in Inner Mongolia, the area of irrigated farmland increased from 0.20×10^6 ha in 1950 to 0.37×10^6 ha in 1973. During this period of intense agricultural development, the area of secondary salinization increased from 0.03×10^6 ha to 0.21×10^6 ha, accounting for 57% of the irrigated area by 1973 (Wang et al. 2002). If reserved farmland is included, secondary salinization lands covered an area of 5.56×10^6 ha—more than half (58.49%) of the total reserved farmland in Xinjiang.[4] At the same time, the area affected by secondary salinization was 40.28% in Gansu, 22.79% in Ningxia, and 9.46% in Inner Mongolia. In the farmlands reclaimed since 1990 in Xinjiang (0.39×10^6 ha) and in Gansu and Ningxia, the groundwater table rose after irrigation, which caused secondary salinization (Wang et al. 2002). For mitigation of salinization, catchment and regional management have been considered, soil improvement and river regulation are coordinated, and drainage and irrigation are integrated by local government. In the arid region, soil salinization is always a key limiting factor for improving land utilization and crop yield and expanding arable land (see Chapter 2).

1.2.3 Rangeland Degradation

Rangeland degradation is the process of declining pasture quality and productivity, which can cause rangeland use to decrease or even disappear. Rangeland degradation is induced by natural factors such as increasing aridity, sand movement, and salinization or by human activities such as overgrazing and excessive cutting of vegetation. Increases in the area of degraded rangeland since the mid-1970s vary between 42% and 87% in Gansu, Xinjiang, and Inner Mongolia. For example, the area of degraded rangeland at the end of the 1970s in Inner Mongolia was 213.4×10^3 ha, covering 36% of usable rangelands. This increased to 387.0×10^3 ha in 1995, making up 60% of the total. In sum, between 1980 and 1995, degraded rangeland had increased by 173.6×10^3 ha at an annual average rate of 11.6×10^3ha, or 1.9% annually.

Human activities and climate change are the key factors causing rangeland degradation. Overgrazing, an imbalance between demand and supply of pasture grass and animals, is the primary driver. Secondary factors are imprudent reclamation of farmland, abusive tree cutting, and mining activity (Wang et al. 2002). Unwise policies also result in rangeland degradation. The investment in pasture land totaled about 100 million yuan each year from 1991 to 1995, but this represented only 0.45 yuan allocated to each hectare of usable pasture land (Li 1997). Local government overly emphasized the short-term utility of rangeland as an animal husbandry base and overlooked its ecological function. As a consequence of underinvestment and over-exploitation, the output of the pasture ecosystem outpaced the input, leading to degradation.

1.3 Nature and Eco-reconstruction

Eco-reconstruction, which includes afforestation, greening projects, eco-restoration, and enclosure, is an important component of the development strategy for the arid region of northwest China (see Chapter 18). The distribution of the main types of ecosystems on the terrestrial surface is determined, in part, by the combination of temperature and moisture conditions. These and other natural limitations determine, or should determine, what human interventions are feasible.

1.3.1 Afforestation and Greening Projects

Large environmental projects are best achieved by working within the laws of nature. The idea that greening or eco-reconstruction equals afforestation is the result of a lack of understanding of natural zonality in climatic conditions, or underestimating its implications. Generally, there are natural forests and therefore land suitable for afforestation in the humid and subhumid monsoon areas in east China. In arid and semiarid regions, however, trees can only grow in limited areas with unusually favorable conditions, indicating that afforestation of large areas is not feasible. Some scientists and policy makers believe that forest coverage can be taken as one of the indices indicating regional sustainable development, whether in humid or arid regions. This point is open for debate. Taking the northwest arid region as an example, areas suitable for afforestation are limited, and forest coverage in some provinces is less than 5%. The imposition of large-scale afforestation to achieve the same forest coverage that exists in humid and subhumid regions would violate the principle of natural zonality. Therefore, the harmonization of environment and development in arid and semiarid regions should be in line with local conditions. Policy makers and practitioners should accept low forest coverage and avoid pursuing unrealistic afforestation targets (Zheng 2000).

Greening projects, another means of eco-reconstruction, were built along airport highways and other areas by drawing water for flood or spray irrigation in arid northwest China. However, the projects have not met expectations. Most greening projects have brought about no tree belt, but instead more vulnerable vegetation and soil. Small-scale forest shelterbelts may be established along the edge of oases, but their role should not be exaggerated; they can help prevent desertification by reducing blowing sand, etc., but only to a certain degree. In view of the natural environment, large-scale afforestation has not proven helpful for sandstorm prevention and was contraindicated by water shortage conditions (Wang et al. 2002).[5] Large-scale afforestation under such conditions would completely violate natural zonality (Chen 2005).

1.3.2 Eco-restoration and Enclosure

The objective of desertified land rehabilitation is not a single-faceted emphasis on increasing vegetation cover. It is designed to promote the natural regeneration and restoration of vegetation, the growth of herbs and shrubs in desert areas, and the containment of desertified land (Man et al. 2005). Desertification in China is zonal; desert vegetation in the arid region is strongly adapted to an extreme habitat, but once destroyed, its self-restoration ability is restricted compared to more mesic regions. Still, in general, the basic principle for rehabilitation is to protect existing vegetation and make full use of the self-adjustment and self-restoration function of the ecosystem (Ma et al. 2005).

Research conducted at the Shapotou Desert Research and Experiment Station, which monitors desertification processes and experiments with vegetation to thwart desertification, has revealed that water from rainfall would infiltrate the soil slowly and be temporarily stored near the surface due to the crust formed on sand dunes. This appears to be the main reason for the deterioration of planted *Caragana korshinskii* stands and the survival of shallow-rooted vegetation dominated by *Artemisia ordosica* (Feng et al. 1995). Observations of desert vegetation in northeastern Gulang, a county in Gansu province at the southern edge of the Tengger Desert,[6] revealed that deep-rooted vegetation such as *Hedysarum scoparium*, *Caragana korshinskii*, and *Artemisia sphaerocephala* degrades gradually because of soil surface crust, and *Artemisia ordosica* becomes the single dominant desert vegetation. Therefore, enclosing animals, forbidding grazing, etc., are effective ways to realize sand fixation (Wang et al. 2006).

The Gurbantünggüt Desert in Xinjiang presents another argument for enclosure. The desert is characterized by fixed and semi-fixed sand dunes on which *Haloxylon persicum*, *H. ammodendron*, and spring ephemeral plants grow well (Fig. 1.3). It is an important genetic base among arid regions of the temperate zone. Vegetation destroyed by imprudent human activities would recover to the corresponding climax community quickly if proper enclosure measures were adopted.

Fig. 1.3 *Haloxylon* spp. in the Gurbantünggüt Desert

1.3.3 Nature Reserves

The desert has its own characteristic processes of formation, evolution, and development. The development experience of the arid region in northwest China since the 1950s has taught many lessons in land management. For example, in the region's Junggar Basin, natural vegetation was healthy originally, but now moving dunes are widespread due to unreasonably large-scale land reclamation, overcutting of vegetation, and overgrazing. Efforts to prevent and control desertification, such as establishing an arbor and shrub protection belt and allowing the natural rehabilitation of vegetation in some areas, have achieved some success. However, most interventions have involved neutral or even negative measures.

The Tian Shan mountains, which traverse the central Xinjiang Autonomous Region, are of special importance for the arid region of northwest China, as they are home to 15 nature reserves occupying an area of 10.44×10^3 km^2. The range is significant for protecting rare fauna and flora and preserving virgin natural ecosystems and environments such as glaciers, forests, and meadows, which perform the natural function of conserving water and soil and regulating regional climate (Hu 2004). The national government should take actions to enhance the natural protection of other areas, such as the Gurbantünggüt Desert, and identify special areas for nature reserves and national desert parks (Wang et al. 2002).

1.4 Water and Land Resources for Sustainable Development

Environmental management and eco-reconstruction have a close relationship with regional sustainable development. Issues including the exploitation and utilization of water and land resources and regional harmonization between development and environment have been recognized, to a degree, in the economic development of the arid regions of China.

Fig. 1.4 Oasis in the piedmont of the north Tian Shan Mountains

1.4.1 Land Reclamation

Land reclamation (modification from a natural state to one of human use or occupation) was the main thrust of land use in the development of the northwest arid region from the 1950s to the 1960s. Great achievements in land reclamation have been obtained, but its negative effects on the environment are obvious. Artificial oases have been constructed and enlarged at the cost of original desert vegetation (Fig. 1.4). From 1950 to 1998, 3.93×10^6 ha of land was reclaimed in Xinjiang, and total farmland reached 5.14×10^6 ha including farmland reclaimed before 1950. However, in 1998 the area of active farmland was just 3.31×10^6 ha, and abandoned farmland amounted to 1.83×10^6 ha or 35.6% of the total once cultivated. The rate of abandonment has increased to 46.5% based on more recently reclaimed land, most of which has reverted to wasteland except for a small amount occupied by structures (Chen 2004). Severe salinization occurred in the reserved unreclaimed land, making it unsuitable for cultivation. In recent years, authorities in Xinjiang have drafted a plan for reclaiming more than 1–2 million ha of land, which has raised concern. In the future, emphasis should be put on improving grain yield instead of on reclamation of additional marginal lands without planning.

1.4.2 Water Resources

Many mountain glaciers exist in the northwest arid region that are important water sources for the development and maintenance of large oases in northwest China. The water that originates from melting snow and ice high in the Tian Shan, Kunlun, and Pamir ranges that border the Taklimakan Desert, for example, ensures the existence of these oases. The expansion of irrigated land attributed to the intensification of agricultural production, since 1950 in particular, explains the degradation of the oasis ecosystems.

The main issues encountered in water resource management in the region include wasteful usage, low efficiency, and poor management policy. More research on technologies favorable to arid areas is required to save irrigation water. In terms of agricultural development, plastic film mulch is promising; it helps crops because it slightly aids absorption of sunlight while reducing daily extremes in soil temperature and retaining soil moisture. Most crops can be cultivated with this technology. However, further research should be conducted on the effects on soil and soil organisms, particularly microbes, after this habitat change (Huang 2003b). Due to the over-exploitation of groundwater for irrigating land in northern Xinjiang, the water table has dropped rapidly, severely threatening the ecological viability and sustainable development of oases.

The suggestion of transferring water from east to west, reconstructing the northern desert, was based on the assumption that applying sufficient water resources could transform the desert into fertile farmland, which would produce quality grain, cotton, and fruit. Some proposals asserted that every scientific and technological requisite was present for transferring 40×10^9 m^3 of water from the Yarlung Zangbo River to Xinjiang (Li 2005). However, inherent limitations in the arid region could not be overcome by simply transferring water because objective natural zonality could not be changed so readily. Prudent planning for water transfers in arid regions should aim mainly at supplying water for cities, industry and mining, etc., rather than for reclamation and agricultural development. Otherwise, natural vegetation will be destroyed and secondary salinization will become more severe. Apart from risks to the natural environment, any proposal for large-scale and long-distance water transfers to the arid region of northwest China must consider a series of social and economic questions, such as feasibility, market demand, and cost effects (Zheng 2000) (see Chapter 6).

1.4.3 A Crisis: The Minqin Oasis

Nature is an interdependent and interacting entity, the significance of which is clear when considering the upper and lower reaches of one river basin. The Minqin oasis in the lower reaches of the Shiyang River has seen a long history of development. In the early twentieth century, sandy desertification was severe, with 17.4×10^3 ha of land buried under sand. From the end of the 1950s to the beginning of the 1980s, biological and mechanical measures were adopted to control desertification. An oasis shelterbelt system consisting of trees, shrubs, and herbs was formed, which has secured the livelihoods of local residents (Gao et al. 2004). Minqin has not been threatened by shifting sand dunes or heavy deposition in the last few decades and is considered an advanced county in its achievements in combating desertification. In spite of this, the county has its own limitations regarding the success of these measures; to ensure steady improvement, steps should be taken at the county level to analyze suitable regions and conditions, monitor development processes, and predict future development trends.

A large area of protective forest of *Elaeagnus angustifolia* was established in the Minqin oasis in the 1950s. The forest covered 17×10^3 ha, and shrubland claimed 27×10^3 ha in 1991. Due to a rapidly declining groundwater table, 6×10^3 ha of the

Fig. 1.5 Died and withered shelterbelt of *E. angustifolia* in the Minqin oasis

forest has died, as has more than 8×10^3 ha of planted shrubland (Fig. 1.5) (Shen et al. 2005). It is thus clear that, in arid areas, it is not feasible merely to pursue forest coverage when establishing a shelterbelt. Sustainable use of water resources must be ensured to prevent a dramatic decline in the groundwater table. Such a decline would adversely influence agriculture, animal husbandry, and the protective forest itself, eventually resulting in sand encroachment.

The utilization of water resources in the Shiyang River lacked long-term planning and uniform management. The Wuwei basin in the middle reaches of the Shiyang River has been over-exploited, resulting in deficient water supplies, abandoned farmlands, and environmental imbalance in the basin. Runoff flowing into the Minqin oasis decreased from 588×10^6 cubic meters per year ($m^3\ a^{-1}$) in the 1950s to $110\times10^6\ m^3\ a^{-1}$ at the beginning of the twenty-first century. The rapid increase in the local population exerted great pressure on resources and the environment; cultivated land in the Minqin oasis increased by an area of 27.5×10^3 ha between 1987 and 2001. Tremendous waste of water resources, such as flood and ditch irrigation at rates of 10.05×10^3 cubic meters per hectare ($m^3\ ha^{-1}$), led to a lower water utilization efficiency (Ji 2004). To supply this irrigation, annual over-exploitation of groundwater followed. By the beginning of the 1990s, groundwater over-exploitation reached $3.63\times10^9\ m^3$ annually. Regional groundwater tables have declined by about 4–17 m, and three 1,000-km^2 cones of depression have formed. The groundwater table in the center of one depression recently declined by 0.6 m–1.0 m annually (Yuan 1991). Due to the decreasing groundwater table, concentrations of dissolved minerals have increased, which has brought about soil salinization, vegetation degradation, and sand dunes. Regulation and control of cultivation and water use are needed as soon as possible in the lower reaches of the Shiyang River to ensure sustainable production and preserve the remaining natural environment.

Further desertification of the Minqin oasis, still a peripheral shelter to hold back the region's Tengger and Badain Jaran deserts, would inevitably threaten the Wuwei oasis (Feng 1992). Unbalanced development of the regional economy has brought about irrational distribution of resources among different areas, which is the basic reason for sandy desertification in the lower reaches of the Shiyang River. Moreover, it has led to environmental degradation in the middle reaches of the river (Xue et al. 2005). Holistic, unified planning among the upper, middle, and lower reaches of the basin should be implemented to achieve a fair, balanced, and sustainable arrangement. Integrated management of sandy desertification, eco-reconstruction, and regional development should be coordinated to achieve the harmonized development of resources, environment, and economy in one basin.

1.5 Reconciling Development with Nature

The development of the northwest arid region of China is a long-term process. Finding ways to balance the relationship between humans and nature is extremely important in this complex and vulnerable environment. Effective measures should be taken to prevent further land degradation, rehabilitate the land, take advantage of its potential, and promote regional sustainable development while recognizing that rehabilitation strategies for various degraded lands may be quite different. When proposing eco-reconstruction projects in desert regions, it is not appropriate to attempt large-scale afforestation or increase forest cover with inevitably limited water resources. Measures such as eco-restoration, enclosure, and natural conservation are helpful for environmental management that complement natural conditions. Moreover, the utilization of land and water resources, as well as the coordination between economic development and the environment, should receive more attention in large regional development plans if they are to succeed and remain sustainable.

AcknowledgmentsWe would like to acknowledge the support of the Faculty of Resources and Environment Science of Xinjiang University, which supplied the necessary information. This work was supported by the Natural Science Foundation of China (Grant No. NSFC40471059).

Notes

1. Potential evapotranspiration is the combination of evaporation and transpiration, often considered to be the water demand of a short crop or grass without water deficiency.
2. Provinces or autonomous regions.
3. Xinjiang, Inner Mongolia, Gansu, and Ningxia are the main provinces of northwest China.
4. Reserved land refers to land that is not cultivated currently but can be in the future.
5. Therefore the “three-north shelterbelt system” should be reconsidered (Wu and Pan 2002). The system covers an area of 3.95×10^6 km^2, of which 55% is desert and 20% is steppe and desertified steppe.
6. Average annual precipitation in the Tengger Desert is only 175 mm and groundwater is at a depth of 67 m.

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Chapter 2
Remote Sensing Assessment of Salinization Impacts in the Tarim Basin: The Delta Oasis of the Ugan and Kuqa Rivers

Tashpolat Tiyip, Gregory N. Taff, Hsiang-te Kung, and Fei Zhang

Abstract Extracting information about saline soils from remote sensing data can be useful, particularly given the environmental significance and changing nature of these soils in arid environments. One interesting case study is the delta oasis of the Ugan and Kuqa rivers in China's Xinjiang region, which was studied using a landsat enhanced thematic mapper plus (ETM+) image collected in August 2001. In recent years, decision tree classifiers have been used successfully for land cover classification from remote sensing data. Principal component analysis (PCA) is a popular data reduction technique used to help build a decision tree; it reduces complexity and can help improve the classification precision of a decision tree. A decision tree approach was used to determine the key variables to be used for classification and ultimately extract salinized soil from other cover and soil types within the study area. The third principal component (PC3) is an effective variable in the decision tree classification for salinized soil information extraction. The PC3 was the best band to identify areas of severely salinized soil; the blue spectral band from the ETM+ sensor (TM1) was the best band to identify salinized soil with the salt-tolerant vegetation of tamarisk (*Tamarix chinensis Lour*); and areas comprising mixed water bodies and vegetation can be identified using the spectral indices Modified Normalized Difference Water Index (MNDWI) and Normalized Difference Vegetation Index (NDVI). Based upon this analysis, a decision tree classifier was applied to classify land cover types with different levels of soil saline. The overall accuracy of the classification was 94.80%, which suggests that the decision tree model was a simple and effective method with relatively high precision.

Keywords Classification · Decision tree · Extraction of salinized soil information · Karhunen–Loeve transform · NDVI

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G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
DOI 10.1007/978-90-481-2776-4_2, © Springer Science+Business Media B.V. 2010

2.1 Soil Salinization and Monitoring Salt-Affected Areas

Remote sensing of salt-affected surfaces provides evidence for the presence of salts either directly on bare soils with efflorescence and salt crusts (generally occurring in areas already affected by severe salinity problems) or indirectly by affecting vegetation type and growth or moisture conditions (Mougenout et al. 1993). The growth of certain vegetation species can be related to different salinity levels, and early signs of stress due to salinity can be identified in healthy vegetation (e.g., crop yield decrease), as plant growth is impaired because of the high osmotic pressure of excess soluble salts (Pang et al. 2004).

Soil salinization is the most common land desertification and land degradation process, and it particularly occurs in arid and semiarid regions (United Nations Environment Program (UNEP) 1991), where precipitation is too low to maintain a regular percolation of rainwater through the soil. Under such a climatic condition, soluble salts accumulate in the soil, influencing soil properties. This causes a decrease in soil productivity, limits the viability of crops, constrains agricultural productivity, and, in severe cases, leads to the abandonment of agricultural soils (Lu et al. 2001) (see Chapters 1, 3, and 4). In addition, it also poses a major environmental hazard by degrading the quality of water, decreasing wildlife diversity, degrading roads, and destabilizing buildings.

Salinization of soils is an important environmental problem in China and throughout the world. For instance, within the European Union and candidate countries, between 1 and 3 million hectares (ha) is affected by soil salinization (European Commission 2003). Serious soil salinization problems exist in Spain's Ebro Basin, for instance, where about 310,000 ha of agricultural land is affected by salts (Alberto et al. 1983), and more than 28% of the irrigated area is degraded by salinization and/or sodification (Herrero and Aragüés 1988). The European Commission, conscious of this serious threat, has recommended the urgent implementation of a network to collect reliable information on the status of the basin (European Commission 2003). In addition, the European Commission intends to develop actions and strategies to combat that threat. To do so, however, requires a rapid, cost-effective technique for assessing soil salinity. The consistent identification of the salinization process is essential for sustainable soil management. Remote sensing classification is an effective means for monitoring soil salinization dynamics over large areas.

A variety of remote sensing data and techniques have been used widely for identifying and monitoring salt-affected areas with varying degrees of success. Common data sources used for these purposes are aerial photographs, video images, infrared thermography, and visible and infrared multispectral and microwave images (Metternicht and Zinck 2003; Qi-sheng He et al. 2007a; Campbell 2002; Foody 1992; Moody et al. 1996; Li and Zhang 2005; Liu et al. 2004; Luo 2001). The extraction of information regarding the levels of soil salinization has been based primarily on its spectral response characteristics. Compared with farmland unaffected by salinization, salinized soils have strong reflection in the visible and near-infrared

(NIR) spectral bands; the higher the degree of soil salinity, the more powerful the reflection in these bands (Rao et al. 1995).

The 1–3–5 band combination (blue, green, mid-infrared) was found to be the best among all the 20 three-band combinations of the reflective thematic mapper (TM) bands for delineating salt-affected soils. This combination ranked first in terms of Optimum Index Factor (OIF) values as well as the accuracy of mapping salt-affected soils. The other band combinations, however, did not show any consistency with respect to the correspondence between image variance as measured by OIF values and the mapping accuracy (Dwivedi and Rao 1992).

Different image transform methods such as principal components analysis (PCA) and hue–intensity–saturation (HIS) have been used to classify salt-affected soils (Dwivedi and Sreenivas 1998). PCA is a technique that transforms the original remotely sensed data set into a substantially smaller and more user-friendly data set by interpreting a set of uncorrelated variables that represent most of the information presented in the original data set. Principal components are derived from the original data in which the first principal component accounts for the maximum proportion of the variance of the original data set, and subsequent orthogonal components account for the maximum proportion of the remaining variance (Holden and LeDrew 1998; Zhao and Maclean 2000).

HIS, meanwhile, is the color coordinate system that is based on a hypothetical color sphere. The circumference of the sphere represents hue, which is the dominant wavelength of color. Hue values begin with zero at the midpoint of red tones and increase counterclockwise around the circumference of the sphere to conclude with 359 degrees adjacent to zero. The vertical axis represents intensity that varies from black to white and is not associated with any color. Finally, saturation describes the dominance of a particular hue, such that one hue dominates in a color with high saturation and multiple hues mix in a color with low saturation.

2.2 Study Area

Soil salinization in Xinjiang province, China, is occurring due to the unique local conditions of climate, topography, hydrology, geology, vegetation, and human activities. There has been little remote sensing research on salinized soils in the region, particularly in the extreme arid areas with the salt-tolerant vegetation species of tamarisk (*Tamarix chinensis Lour*). The spectral response of salinized soils can differ significantly depending on the factors that led to the salinization, so the most appropriate classification method may depend on the study region.

Located in the north of the Tarim Basin and the Taklimakan Desert of Xinjiang province, the delta oasis of the Ugan and Kuqa rivers covers about 53,500 km^2 and consists of three oases: Kuqa, Toksu, and Shayar (Fig. 2.1). The mean range of elevation is between 920 and 1,100 m, and the climate exhibits extreme aridity; the average annual precipitation is 51.6 mm and the average annual evaporation is

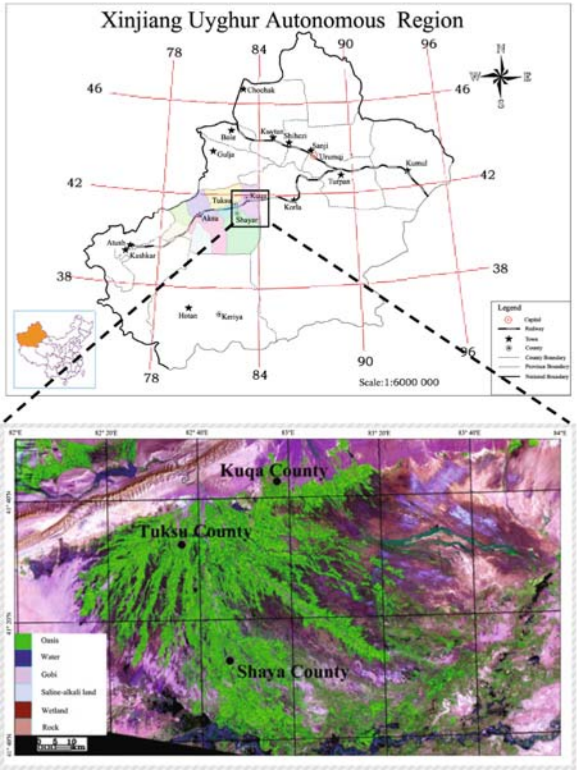

Fig. 2.1 Study area location. (See also Plate 1 on p. 335 in the color plate section)

2,123.7 mm; the ratio of evaporation to precipitation is about 40 to 1. A hydrological imbalance in the depression, underpinned by intensive agricultural practices, the overuse of irrigation, and improper drainage systems has caused the water table to rise in the topsoil. This rise of the water table has led to increased salinization and degradation of the relatively limited soil resource base (Datta and Jong 2002).

The type of soil in the study area is mostly sub-sand and sub-clay. The classification system used was established by researchers in Xinjiang (Zhao et al. 2004; Metternicht 2003); the pH value of the soil is about 8.0, and the main component of the saline in the soil is chloride (Fig. 2.2). The classification of the salinized soil in the study area is shown in Table 2.1 (salt content in a 0–10 cm soil layer).

2.3 Image Data

The delta oasis of the Ugan and Kuqa rivers was studied using a Landsat Enhanced Thematic Mapper Plus (ETM+) image collected August 6, 2001. The 30 m spatial resolution ETM+ image (path 145 row 31) had been processed with geometric correction and coordinate conversion. The atmospheric correction method for the Landsat ETM+ data as proposed by Ouaidrari and Vermote (1999) was employed

Fig. 2.2 Sample photos showing varying degrees of soil salinization. **a**: Slightly salinized soil, salt content of surface soil is 15 g kg^{-1}–45 g kg^{-1}, vegetation cover is generally about 15% **b**: Moderately salinized soil, salt content of surface soil is 45 g kg^{-1}–75 g kg^{-1}, vegetation cover is generally about 5% **c**: Severely salinized soil, salt content of surface soil is 75 g kg^{-1} or more, vegetation cover is generally 0–1%

Table 2.1 Scheme for classification of remote sensing image of the study area

Class	Definition
Sandy soil	Sandy soil or gravel
Water body	River, reservoir, lake, or water channel
Non-salinized soil	Salt content of surface soil is 0–15 g kg^{-1}
Slightly salinized soil	Salt content of surface soil is 15 g kg^{-1}–45 g kg^{-1} (thickness of salt crust: 0–2 cm)
Moderately salinized soil	Salt content of surface soil is 45 g kg^{-1}–75 g kg^{-1} (thickness of salt crust: 2–5 cm)
Severely salinized soil	Salt content of surface soil is 75 g kg^{-1} or more (thickness of salt crust: 5–10 cm)

to convert the top-of-atmosphere (TOA) reflectance to surface reflectance. This correction method is based on the 6S radiative transfer code and can make corrections for atmospheric and adjacency effects. Landsat ETM+ data were used because they are inexpensive, possess a high monitoring frequency (therefore this method can be used to track changes in soil salinity over time), and cover large areas appropriate for developing soil conservation planning for a large geographic area. The Landsat ETM+ has a temporal revisit time of 16 days with six visible/near-infrared/middle-infrared bands and one thermal band (at 60 m spatial resolution). In this study, a large and representative region of salinized soils was selected. The gravel region of the Gobi Desert in the northern part of the oasis was excluded from the study so that the image size ultimately selected was 2,027 × 2,942 pixels, and the coordinates were 41°8′–41°39′N latitude and 82°58′–83°57′E longitude; the study area was 4.84×10^7 ha.

2.4 Extraction Method of Salinized Soil Information

Raw data acquired from ground-, air-, or satellite-borne sensors are usually transformed to allow for better discrimination between saline and nonsaline soils or among salinity classes. A variety of transforms of remote sensing data have been used in soil salinity studies, including best band selection; principal components analysis; the Kauth–Thomas transform; intensity–hue–saturation transformation; image ratioing; image differencing; and pattern recognition techniques using the maximum likelihood classifier, neural networks, decision trees, unmixing of surface features, fuzzy classification, and radar backscattering inversion techniques (Castrignanò et al. 2008; Pulkkinen and Koivisto 2008; Jenhani et al. 2008; Tiyip et al. 2007; Qi-sheng He et al. 2007b; Qi-sheng He et al. 2006). Decision tree algorithms provide one of the most popular methodologies for symbolic knowledge acquisition (Pal and Mather 2003).

A symbolic decision tree, along with a simple inference mechanism, has been praised for comprehensibility. A decision tree classifier is a classification method that groups each pixel in an image based on a hierarchical set of decision rules. In this case, the decision rules are based on some function of the spectral data. The decision rules are determined by an expert for maximum separability of classes of interest, and are based upon the known spectral properties of ground truth data. Decision tree classifiers—such as the one used in this study—in which the decision rules are binary (that is, the outcome of the decision puts each pixel in one or another branch of the decision tree), are called binary decision trees. Common functions of the data upon which decision rules are typically based are the raw (or radiometrically corrected) brightness values, indices such as Normalized Difference Vegetation Index (NDVI), principal components derived from the original spectral bands, and other simple arithmetic functions of the spectral data. The expert determination of appropriate decision rules is key for the success of a decision tree classifier.

A knowledge-based expert system can be defined as “a system that uses human knowledge to solve problems that normally would require human intelligence” (PC AI 2002). Such a system incorporates the ability to “solve problems efficiently and effectively in a narrow problem area” (Waterman 1986) and “to perform at the level of an expert” (Liebowitz 1988). Expert systems represent the expert’s domain (i.e., subject matter) knowledge base as data and rules within a computer. The rules and data can be called upon when needed to solve problems, and a different problem within the domain of the knowledge base can be solved using the same program without reprogramming.

Knowledge-based expert systems continue to be used extensively in remote sensing research. Moller-Jensen (1997) used texture and an expert system inventory of urban land cover. Muchoney et al. (2000) used a decision tree classifier to extract land cover information from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data of Central America. Tso and Mather (2001) summarized numerous applications of hierarchical decision tree classifiers—the most general type of knowledge-based classifier (Hansen et al. 1996; 2000). Pal and Mather (2003) assessed the effectiveness of decision tree methods for land cover classification. Krapivin and Phillips (2001) used an expert system to model what it would take to stabilize the Aral Sea and Caspian Sea water levels to the 1960 levels within 10 to 12 years. Expert systems may also be used to detect change in complex heterogeneous environments (e.g., Stefanov et al. 2001; Yang and Chung 2002; Stow et al. 2003).

2.4.1 Data Characteristic Selection for the Extraction of Salinized Soils Information

2.4.1.1 NDVI

NDVI, defined as the value of the difference between the reflectivity in the near-infrared band and red band divided by their sum, $NDVI = (NIR - R)/(NIR + R)$, was used in this study for decision rules (see Chapter 4). NDVI was used to distinguish between degrees of soil salinity and between vegetative and non-vegetative land cover types.[1] In the delta oasis of the Ugan and Kuqa rivers, NDVI was greater than zero only for the areas with poplar (*Populus euphratica Oliv)* and farmland, while the value for all other land cover was less than zero. The distribution of NDVI for salinized soils allows a threshold to be identified; pixels are categorized as salinized soils below the threshold and as vegetation above it (Dong-min et al. 2001).

Soil salinity can restrain vegetation growth; usually vegetation coverage is low when soil salinity is high and vice versa. But since NDVI reflects the state of vegetation coverage, the level of soil salinization on vegetative land can be measured using NDVI. In order to find the correct thresholds for determining the levels of soil salinization, the correlation of NDVI and the degree of soil salinity was analyzed. The analysis was based on 84 field sampling points, and the salt content was measured in a chemistry laboratory. Field points were geolocated using a Global Positioning System (GPS), and the locational accuracy was between 5 and 10 m. The result showed that the correlation coefficient is strongest when the soil salt content is 10–67 g kg^{-1} (gram per kilogram) and the correlation coefficient was –0.875; the significance level of the correlation coefficient was 99%. The curve analysis of NDVI and the degree of soil salinity could be processed to find the appropriate thresholds. The result showed that the cubic polynomial with no constant was the best fit, and the result of the curve analysis was as follows: the R^2 was 0.948 and the result of the F test was notable. Based on the formula, $NDVI = 6.31\times 10^{-7}X^3 + 7.91\times 10^{-5}X^2 + 5.14\times 10^{-4}X$, where X is the salt content of the soil, the NDVI value for the threshold for the 15 g kg^{-1} salt content class was -8×10^{-3}, and the corresponding NDVI value of the 45 g kg^{-1} salt content class was -8×10^{-2}.

2.4.1.2 Modified Normalized Difference Water Index (MNDWI)

McFeeters (1996) presented the Normalized Difference Water Index (NDWI), which was applied as follows:

$NDWI = (Green - NIR)/(Green + NIR)$, where Green is the digital number (DN) of the green band (which may refer to the raw DN or the DN of the radiometrically corrected band), and NIR is the digital number of the near-infrared band in the Landsat ETM+ image, respectively representing the TM2 and TM4 bands. Note that Gao (1996) defined a different NDWI index using the NIR and MIR (mid-infrared) bands. The reflection of the water gradually weakens from the visible to the infrared portion of the electromagnetic spectrum, and the absorption in the near-infrared and middle-infrared wavelengths is very strong, almost without reflection. Therefore, the NDWI, composed of the contrast of visible and near-infrared bands, highlights the water body information in images. As the reflectivity of the vegetation in the near-infrared band is generally strongest, the use of the ratio of green and near-infrared bands could clearly distinguish vegetation information and also highlight water body information.

However, when McFeeters presented the NDWI, the only factor taken into account was the vegetation, and another important category—the surface soil and buildings—was neglected. Xu (2005) modified the index of NDWI and presented the Modified Normalized Difference Water Index (MNDWI). MNDWI was applied as follows:

$MNDWI = (Green - MIR)/(Green + MIR)$, where Green is the digital number of the green band and MIR is the digital number of the middle-infrared band in the Landsat ETM+ image, respectively representing the TM2 and TM5 bands. The analysis on the delta oasis of the Ugan and Kuqa rivers showed that when the NDWI was used to extract water body information, the water body was severely confused with gravel and desert. The MNDWI can depress the built-up/gravel/desert land information effectively while highlighting water information and can therefore accurately extract the water body information. The MNDWI has achieved excellent results (Xu 2005). When the MNDWI was used in the delta oasis study, extraction accuracy of water body information reached 96.5%; therefore, the water body information could be better extracted than when using the NDWI. The MNDWI was selected as the function of the spectral data to be used to distinguish water bodies from other land cover types.

2.4.1.3 Karhunen–Loeve Transform

The Karhunen-Loeve (K-L) transform is also called the principal components transform and the multidimensional orthogonal linear transformation (Small 2004). The main purpose of the Karhunen–Loeve transform is that the most useful information of the original multiband image is concentrated in the minimal number of principal components, and the principal components are uncorrelated (Mei et al. 2001). In other words, the information contained in each of the principal components does not overlap with the others, and thus only the most important principal components (the ones that display the most variability in the data) are used. This eliminates redundant information so that the total volume of data can be greatly reduced, and the information most effective for classification is highlighted. But even if the first principal component contains more than 90% of total variance, as with this study (Table 2.2), it generally can't function well as a substitute for multiband information. Although the first principal component contains most of the information, this information is not necessarily the most useful for distinguishing between certain land cover classes (Dai et al. 2004). Conversely, another principal component may contain little information but may contain the requisite information to distinguish between certain land cover classes. Thus, the principal components used should be selected based on the specific application.

Table 2.2 Principal component eigenvalue and eigenvector matrix of ETM+ image in research area

Principal component	Channels						Eigenvalue	Contribution of variance (%)	Cumulative contribution of variance (%)
	TM1	TM2	TM3	TM4	TM5	TM7			
K-L-1	0.4055	0.3899	0.4567	0.4261	0.4179	0.3446	6650.65	93.21	93.21
K-L-2	−0.0312	−0.0992	−0.3788	0.8493	−0.0402	−0.3505	390.99	5.48	98.69
K-L-3	−0.4295	−0.3124	−0.3264	0.0613	0.5354	0.5665	77.44	1.09	99.78
K-L-4	0.6776	0.0768	−0.6441	−0.2485	0.2410	−0.0158	11.35	0.16	99.94
K-L-5	0.0528	0.2211	−0.2444	0.1516	−0.6739	0.6415	3.03	0.04	99.98
K-L-6	−0.4337	0.8281	−0.2585	−0.0932	0.1579	−0.1603	1.27	0.02	100.00

The Karhunen–Loeve transform was performed on the ETM+ image of August 6, 2001. Results showed that although the first and second principal components contained the most total information, they were not the best band for extracting severely salinized soil information. The value of the third principal component is small for severely salinized soils and water bodies, while it is larger for other land cover types. So, by using a threshold in the third principal component, severely salinized soils and water bodies can be distinguished from other land cover types. Next, the water bodies could be separated from severely salinized soils using the MNDWI. Therefore, the third principal component could be considered the key variable (that is, the most important function of the spectral data) for extracting the information about severely salinized soils.

2.4.1.4 TM1 Band

The sampling points were selected from the range of land cover classes in the Landsat ETM+ image. These points were located using GPS, and ground truth was performed in the field. Statistics were generated to obtain the spectral signatures for the training data of all the land cover types. The results (Table 2.3) show that the DN values of the TM1 (blue) band were similar for desert, gravel, and residential areas. Although the TM1 band alone cannot distinguish among these cover types, the TM1 band could distinguish between these three land cover types and two others—*Populus euphratica Oliv* and agricultural land—which both have relatively lower surface reflectance values in the blue range (TM1). TM1 band surface reflectance values of salinized soil with salt-tolerant vegetation such as *Tamarix chinensis Lour* were between 56 and 80, which was primarily confused with water, *Populus euphratica*, and agricultural land. It was easy to separate water body classes by using the MNDWI and vegetation classes by using the NDVI, and then the salinized soil information with salt-tolerant vegetation of *Tamarix chinensis Lour* cover could be extracted. Note that in Table 2.3, there are three columns of *Tamarix chinensis Lour* (categories 1, 2, and 3), each referring to *Tamarix chinensis Lour* land cover associated with levels 1, 2, and 3 of soil salinization. The TM1 band could be considered the key variable for extracting the information of salinized soils with cover of the salt-tolerant vegetation of *Tamarix chinensis Lour*. The three classes of *Tamarix chinensis Lour,* other vegetation such as *Populus euphratica Oliv*, and water have TM1 mean values that vary between 63 and 73. Other classes are not in this scope; therefore, these land cover types can be separated from the others using only ETM+ band 1.

2.4.2 The Establishment of a Decision Tree Classifier Model

The decision tree classifier model for the extraction of salinized soils information was established through the analysis of spectral characteristics of the primary land cover types in the study area (Fig. 2.3). Decision tree classifications were implemented using the EASI Software in Geomatica Version 9.1 (PCI Geomatics 2003). The chosen threshold values of TM1, K–L-3, MNDWI, and NDVI were the best values determined empirically by running repeated decision tree classification models.

Table 2.3 Descriptive statistics of the spectral properties of the most common land cover types in the study site

	Types	Bare land	*Tamarix chinensis Lour* -1	*Tamarix chinensis Lour* -2	*Tamarix chinensis Lour* -3	Resident	Desert	Gravel	Water	Reservoir	*Populus Euphratica Oliv*	Farm -1	Farm -2
TM1	Min	88	56	60	67	72	92	91	64	42	60	51	48
	Max	163	80	75	78	99	106	118	75	56	80	65	74
	Mean	132.79	63.92	66.4	72.47	83.13	99.8	107.81	70.48	47.89	73	58.27	56.56
	Stdev	10.68	3.02	2.07	1.82	5.01	2.75	4.55	1.72	2.31	3.68	2.23	4.22
TM2	Min	89	50	52	64	62	92	94	69	31	50	45	38
	Max	154	80	67	75	95	108	127	80	48	77	60	70
	Mean	125.03	57.06	59.61	70.07	77.89	100.67	114.7	74.27	38.25	60.78	52.07	49.28
	Stdev	11.33	3.27	2.3	1.97	6.18	2.47	5.43	1.94	3.88	4.34	2.21	5.25
TM3	Min	106	55	59	79	65	111	121	89	24	45	35	30
	Max	183	96	81	95	110	133	165	110	40	96	58	83
	Mean	146.56	65.1	68.32	87.36	89.59	119.75	146.8	100.9	30.98	56.31	45.59	46.7
	Stdev	13.89	4.5	3.48	2.59	8.19	3.48	7.63	3.53	3.9	6.15	3.24	8.14
TM4	Min	78	39	43	59	59	80	95	70	11	67	105	67
	Max	125	72	61	72	100	95	120	80	31	97	151	116
	Mean	101.99	50.86	51.71	65.26	74.19	86.81	109.12	75.87	16.09	82.68	127.82	87.62
	Stdev	9.37	4.29	3.34	1.99	4.93	2.5	4.69	1.58	2.24	4.06	7.4	6.48
TM5	Min	86	17	45	64	59	93	109	19	7	50	54	35
	Max	130	61	70	88	100	113	146	74	24	94	72	90
	Mean	107.52	48.93	56.63	79.27	77.45	102.18	133.57	39.16	11.1	70.66	64.41	56.1
	Stdev	8.43	4.86	4.57	3.9	5.92	3.65	5.2	15.99	1.39	6.13	2.69	6.37
TM7	Min	72	14	36	53	43	86	104	14	6	40	26	19
	Max	110	52	62	82	90	107	136	55	16	78	47	70
	Mean	87.95	38.24	46.79	72.55	67.89	94.79	124.24	28.84	10.13	50	33.1	34.7
	Stdev	5.98	4.31	4.81	4.98	6.47	3.73	5.28	11.6	1.23	7.13	2.52	6.89

Table 2.3 (continued)

	Types	Bare land	*Tamarix chinensis Lour* -1	*Tamarix chinensis Lour* -2	*Tamarix chinensis Lour* -3	Resident	Desert	Gravel	Water	Reservoir	*Populus Euphratica Oliv*	Farm -1	Farm -2
MNDWI	*Min*	−0.08	−0.01	−0.05	−0.12	−0.13	−0.05	−0.12	0.01	0.27	−0.17	−0.19	−0.19
	Max	0.13	0.51	0.1	0.02	0.11	0.04	−0.06	0.6	0.71	0.05	−0.04	0.11
	Mean	0.0	0.08	0.03	−0.06	0	−0.01	−0.09	0.33	0.55	−0.08	−0.11	−0.06
	Stdev	0.02	0.05	0.03	0.02	0.03	0.01	0.01	0.18	0.05	0.03	0.02	0.04
NDVI	*Min*	−0.2	−0.24	−0.2	−0.18	−0.18	−0.19	−0.17	−0.19	−0.46	−0.1	0.29	0.01
	Max	−0.14	0.02	−0.05	−0.1	0.21	−0.1	−0.11	−0.09	−0.1	0.2	0.6	0.53
	Mean	−0.18	−0.12	−0.14	−0.14	−0.09	−0.16	−0.15	−0.14	−0.31	0.05	0.47	0.31
	Stdev	0.01	0.03	0.02	0.01	0.04	0.01	0.01	0.01	0.07	0.05	0.04	0.09
K-L-3	*Min*	−62.93	−20.41	−14.67	−8.52	−20.19	−12.92	5.82	−61.67	−30.9	−12.05	−0.57	−11.78
	Max	9.14	−1.32	1.6	15.88	14.45	5.76	23.8	−9.59	−15.79	21.33	15.5	17.47
	Mean	−36.87	−8.29	−6.91	6.21	−4.52	−3.74	16.27	−41.69	−22.89	3.94	6.26	2.86
	Stdev	8.2	4.02	3.18	3.76	4.59	3.46	2.7	14.76	3.42	4.15	2.44	3.88

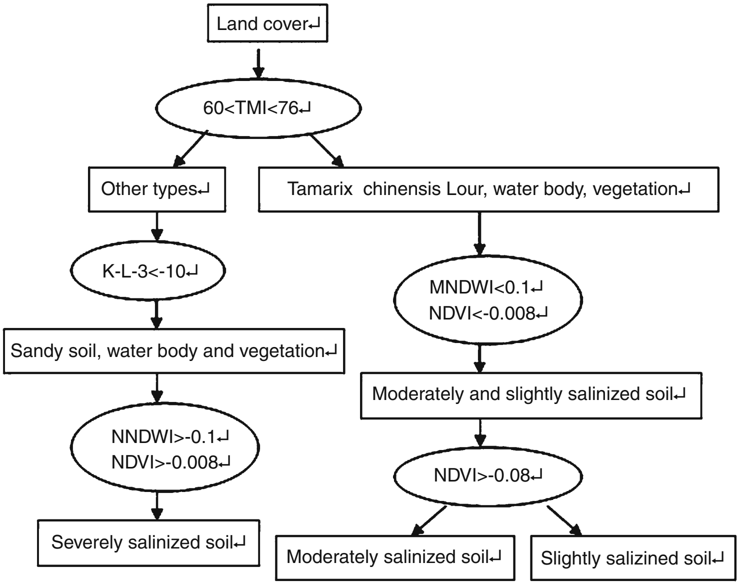

Fig. 2.3 Flow chart of automatic extraction of salinized soil information

2.4.3 Post-classification Processing

A common phenomenon in remote sensing image analysis is a speckling of individual pixels of one land cover type within a larger patch of another land cover type. Scattered pixels of this kind are often called “category noise.” In order to eliminate the impact of category noise, a 3 × 3 window, or grid of Landsat ETM+ pixels, was chosen, and the majority filter function was used to make use of the contextual information from the extraction results. The final results of extraction of salinized soil information show a classified map of soil saline levels (Fig. 2.4)

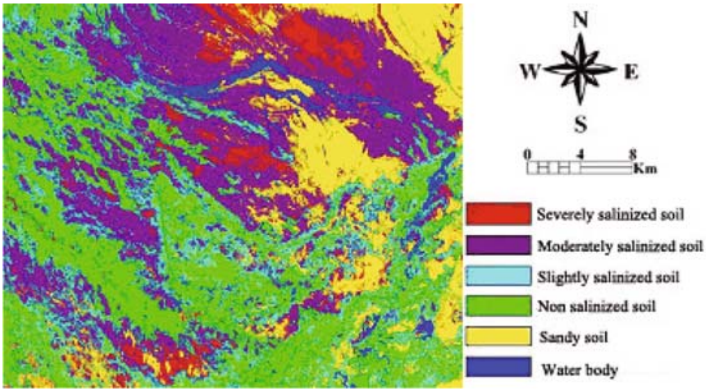

Fig. 2.4 Soil saline levels. (See also Plate 2 on p. 336 in the color plate section)

Table 2.4 Precision validation of extraction of salinized soil information

Types	Producer's accuracy	User's accuracy
Slightly salinized soil	91.89	98.02
Moderately salinized soil	91.97	98.17
Severely salinized soil	90.22	91.35
Non-salinized soil	96.18	91.46
Overall accuracy	94.80	
Kappa coefficient	0.92	

indicating salinized soils are mainly distributed in the ecotone between the oasis and the desert. It assumes a strip shape distribution in the oasis interior, and some moderately and severely salinized soils exist outside the oasis. Severely salinized soils are almost completely surrounded by moderately salinized soils, and slightly salinized soils are located almost exclusively outside the oasis.

2.4.4 Accuracy Assessment

The producer's accuracy shows the proportion of ground sampling points that are correctly classified. The user's accuracy shows the proportion of classified pixels in accord with the actual ground types, as taken from ground truth testing data. The total accuracy reflects the overall proportion of the classification results that are in accord with the actual ground types. There are 84 sampling points, which included samples of all three different soil salt content classes. Of those sampled points, 32 were randomly selected for validation, while the other 52 were used in training.

The overall accuracy and kappa coefficient were then computed (Table 2.4). The kappa statistic is a chance-corrected measure of agreement between the classification and the reference data, if the classification process were to be independent of the reference data (Congalton and Mead 1983). Both the overall accuracy and kappa coefficient were determined using the image processing software Geomatica Version 9.1 (PCI Geomatics 2003).

2.5 The Keys for Extracting Soil Salinization Information

This study proposes a good set of decision rules appropriate for a decision tree classifier that classifies multiple levels of soil salinity in this region with high accuracy based on spectral characteristics of surface targets. Central to the decision tree classifier model for extracting information is the selection of the key variables for class separation. The variables NDVI, MNDWI, K–L-3, and TM1 were selected based on their usefulness for distinguishing between the land cover types in this landscape, and the classification showed success using these four variables in the region. The variables all performed their respective functions well: the NDVI could separate the vegetation information, the MNDWI could separate the water body information, K–L-3 could extract the severely salinized soil information, and the TM1 band could separate the moderately and slightly salinized soil information from severely salinized soils.

The discussion presented is aimed at the extraction of salinized soils with salt-tolerant vegetation of *Tamarix chinensis Lour* cover. Salinized soils are often formed from different processes in different regions, and thus their spectral response characteristics may vary; therefore, the application of this method to other regions for the extraction of salinized soil information requires further research. However, the key findings may be applicable to other regions: remote sensing can be used to locate and map salinized soils and differentiate between levels of salinization, requiring only a minimal amount of field work; a knowledge-based expert decision tree classifier is both useful and comprehensible for separating salinized soil classes with a high level of accuracy; and individual satellite image bands, NDVI, MNDWI, and PCA may all be useful for consideration as decision variables for the decision tree.

AcknowledgementsWe would like to acknowledge the support of the Faculty of Resources and Environment Science of Xinjiang University. This work was supported by the National Natural Science Foundation of China (Grant no. 40261006). The authors wish to express special thanks to Professor Jian-li Ding, Master Hong-nan Jiang (University of Xinjiang), and PhD student Qi-sheng He (Institute of Remote Sensing Applications of the Chinese Academy of Sciences) for participating in this research program, participating in field trips with us, arranging for the collection of data, and carrying out analysis, etc., for this research.

Note

1. It has been shown that NDVI can distinguish between degrees of soil salinity (Toth et al. 1991).

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Chapter 3
Estimating Net Primary Production in Xinjiang Through Remote Sensing

Guanghui LV, Weiguo Liu, Jiangjun Yang, and Entao Yu

Abstract Land cover components of photosynthetic vegetation (PV) and non-photosynthetic vegetation (NPV) were analyzed with satellite remote sensing technology and knowledge of the typical climate–vegetation characteristics of the arid region of Xinjiang in western China. The objective was to develop a Net Primary Productivity-Geography Processing Ecology Model (NPP-GPEM) of solar energy utilization efficiency based on remote sensing and ecological processes that would fit the arid region with reference to such remote sensing–ecological models as the Global Production Efficiency Model (GLO-PEM), Carbon Exchange between Vegetation, Soil, and Atmosphere (CEVSA), and Carnegie-Ames-Stanford Approach (CASA). The terrestrial ecosystem of Xinjiang was taken as an example for this study. Supported by NOAA/AVHRR (Advanced Very High Resolution Radiometer) meteorological satellite remote sensing data and climate data, the annual NPP of Xinjiang's mountain–oasis–desert ecosystem from 1981 to 2000 was estimated at 1 km spatial resolution. Detection and analysis of spatio-temporal change also was performed. The results showed there were great differences in NPP spatial–temporal patterns in various regions. NPP increased in most parts of Xinjiang from the 1980s to the 1990s. The west part of the piedmont plain on the north slope of the Tian Shan Mountains had the largest increase in NPP in north Xinjiang, and Kashi-Shache Delta had the largest increase in south Xinjiang. The spatial distribution of NPP was characterized by a general decrease from north to south and from east to west.

Keywords Arid region · Net primary productivity · Remote sensing · Terrestrial ecosystem · Xinjiang

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G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
DOI 10.1007/978-90-481-2776-4_3, © Springer Science+Business Media B.V. 2010

3.1 Estimating Net Primary Production

The arid region in western China refers to a vast area west of the Helan Mountains and north of the Kunlun Mountains that covers 250×10^4 km^2. This region differs greatly from the monsoon region in eastern China and the Qinghai-Tibet region due to its geographic position, climate, soil, and vegetation. Various types of desert soils and xerophytic and super-xerophytic vegetation developed in the region, which is home to alternating large mountains and basins. This giant mountain–basin system has obvious vertical heterogeneity: oases exist in the lower desert elevations, grassland and forest are distributed in the mountains, and above them sits a large area of ice and snow. The transmission of material, energy, and information is different among various landscapes (e.g., desert and oasis), so the stability of ecosystems is distinct and the ecological environment of this region is fragile. Natural disasters occur frequently. Desertification, salinization, grassland degeneration, water quality deterioration, and biodiversity reduction are becoming more and more serious. In addition, global warming, climatic anomalies, and human activities might exacerbate these problems by impacting the land use/land cover of the mountain–oasis–desert ecosystem.

Heterogeneity of ecological conditions has resulted in many vegetation types and ecosystems in the region. Scarce precipitation and intensive evaporation created a water deficit for vegetation. Adaptation to this extreme arid climate has resulted in xerophytic, super-xerophytic, salt-tolerant, anti-wind, and extreme climate-resistant vegetation able to withstand ecological and environmental stress (Pan and Chao 2001; Cao et al. 2004; Cao and Woodward 1998).

The desert vegetation is widely distributed in the arid region. The desert-scrub patches surrounding the oasis landscape present spatial mosaic heterogeneity, and human activity has caused original habitat to fragment and species diversity to degenerate (Cao et al. 2004, 2002). Though precipitation totals in the region have increased over the past 20 years, desertification in some oases is severe due to economic and population pressure, which causes the heterogeneity of the landscape to degrade. Thus, the non-photosynthetic vegetation (NPV) in various proportions of the desert ecosystem arose with desertification and water stress, while the photosynthetic vegetation (PV) decreased with the change of land coverage and species structure. The photosynthesis production of the community canopy decreased as well (Cao et al. 2004; Asner and Heidebrecht 2005). The function difference in species composition and canopy structure makes one vegetation type differ widely from other vegetation types in remote sensing spectral diagnostics and retrieval methods[1] (Huenneke et al. 2002; Schlesinger et al. 1990).

Net primary productivity (NPP) reflects the carbon-absorbing capacity of vegetation in a terrestrial ecosystem. As the foundation of substance and energy transformation in such an ecosystem, NPP plays a crucial role in environmental evolution (Field et al. 1995). Large-scale geographical and environmental information can be acquired repeatedly with remote sensing technology. Without a doubt, this technology has become a useful tool for real-time retrieval of large-scale surface biomass (Liu 1997; Gao et al. 2004). The application of remote sensing data (NOAA/AVHRR, SPOT/VEGETATION, EOS/MODIS)[2] has made it possible to investigate the carbon cycle, carbon balance, carbon sedimentation, and carbon budget of the terrestrial ecosystem (Prince 1991; Potter et al. 1993). Based on parameterized and process models, an NPP model suited to the region was built by combining physiological and ecological processes with remote sensing technology. The objective was to estimate NPP in this region and analyze its change with a specific NPP model. Vegetation components that absorb photosynthetic active radiation were obtained by remote sensing spectral decomposition, and the absorption efficiency of vegetation on photosynthetic active radiation and incoming radiation was derived from remotely sensed data or climate data. NPP was estimated by an energy conversion factor. In the NPP model, many factors also were considered, such as temperature, soil moisture, drought stress, and the effect of plant respiration on vegetation assimilation.

3.2 Study Area: Xinjiang

Xinjiang, in northwest China, was chosen as the study site[3] because of its typical mountain–oasis–desert ecosystem. Xinjiang extends from longitude 73°32′ to 96°21′E and latitude 34°22′ to 49°33′N and covers an area of 1.66×10^6 km^2. Mountains border Xinjiang on three sides: the Altay to the north, the Kunlun to the south, and the Pamir to the west and southwest. The Tian Shan cut across northern Xinjiang, between the vast Junggar and Tarim basins (Fig. 3.1).

Xinjiang has a predominantly arid and semiarid climate, which is characterized by an abundance of light and thermal resources, scarce precipitation, and intensive evaporation. Annually, the region sees 2,550–3,500 hours of sunshine, 180–220 frost-free days, and a mean temperature of 9–12°C. The northern part of the region is wetter than the south; precipitation averages 100–200 mm and 16–85 mm in the two areas, respectively. Evaporation capacity ranges from 1,500 to 2,300 mm in the north and from 2,100 to 3,400 mm in the south. Desert and oasis dominate the study area.

The ecosystem in the region is fragile, as it is highly susceptible to drastic climate change and short-term climatic fluctuation. Vegetation is made up of few species with low coverage (Cao et al. 2004).

3.3 Research Method

3.3.1 Data Source

The remote sensing data used in this study were NOAA/AVHRR images from Pathfinder Data Sets. The substellar point of NOAA/AVHRR is 1.1 km. The satellite scans the globe twice a day and images of the terrestrial surface can be obtained once every 10 days when clouds are not present. AVHRR has five spectral channels: 0.58–0.68 μm, 0.725–1.1 μm, 3.55–3.93 μm, 10.3–11.3 μm, and 11.5–12.5 μm. The image data of channels 1, 2, 3, 4, and 5 were used in the study for the period

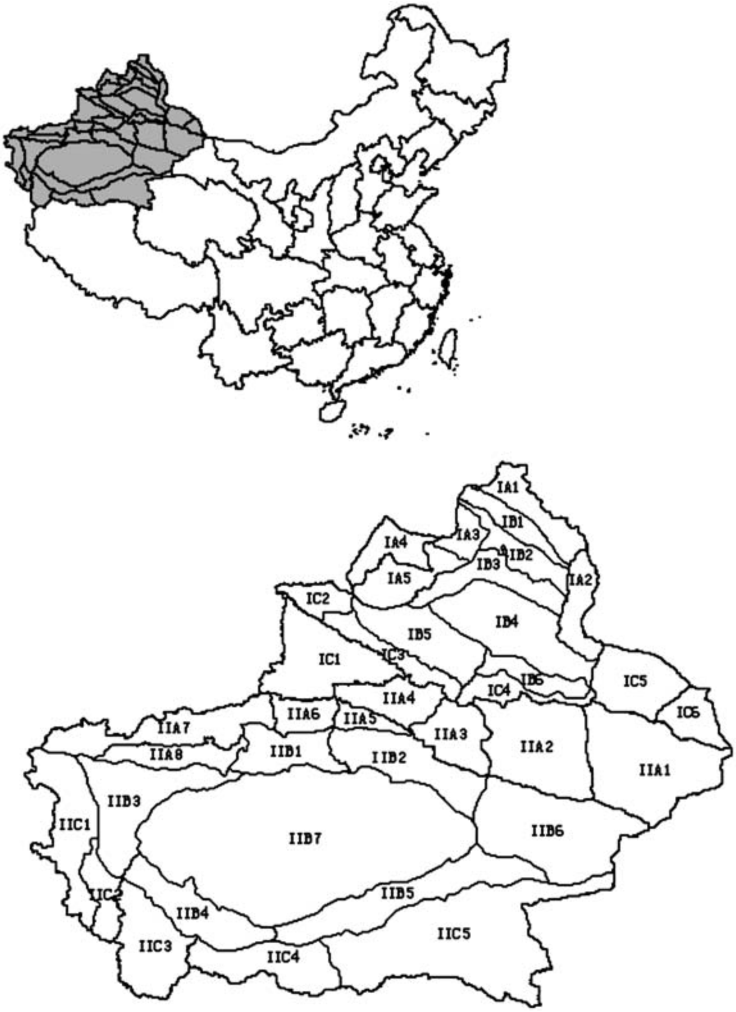


Fig. 3.1 Location of the study area in China

1981–2000 to estimate the annual NPP of Xinjiang's terrestrial ecosystem. Air temperature, precipitation, and total solar irradiance data were obtained from the China Meteorological Administration.

3.3.2 Development of NPP-GPEM Model

Vegetation in arid environments obviously suffers from severe water stress. In the study, PV and NPV were separated by vegetation canopy structure with remote sensing-mixed pixel decomposition. A geographical production efficiency model

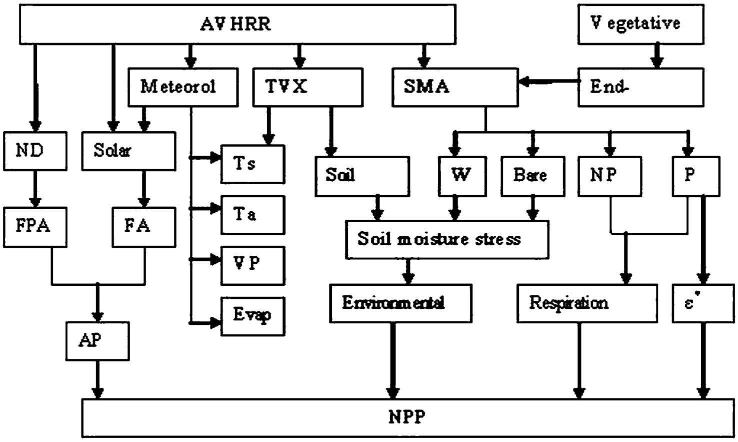


Fig. 3.2 Flowchart of NPP-GPEM model

(NPP-GPEM) fitting the region was built based on such common models as the global production efficiency*** model (GLO-PEM), carbon exchange between vegetation, soil, and atmosphere (CEVSA), and the Carnegie-Ames-Stanford Approach (CASA) patterns (Asner and Heidebrecht 2005; Field et al. 1995; Gao et al. 2004; Prince 1991; Potter et al. 1993; Goetz and Prince 1996). Figure 3.2 shows the framework of the NPP-GPEM model.

Monteith (1972, 1977) brought forward the light use efficiency model in 1972. Light use efficiency (LUE) is the ratio of latent chemical energy contained in dry matter produced to photosynthetic active radiant energy per unit area within the same period. NPP depending on LUE is regulated by many environmental factors such as air temperature, soil moisture, and atmospheric water vapor pressure differences that influence the photosynthetic capacity of plants. These factors are considered to compute maximum LUE and then estimate NPP in the remote sensing model. For example, GLO-PEM is a LUE model that considers ecological processes such as plant photosynthesis and autotrophy respiration (Prince 1991; Potter et al. 1993; Goetz and Prince 1996; Sun and Zhu 2000; Tao et al. 2003). The model is totally driven by remote sensing data. Another example is the CASA model (Monteith 1977; Sun and Zhu 1999; Running et al. 1996; Prince 1995), which is the first model to use the efficiency model idea in global-scale productivity research.

Besides global-scale models, Prince et al. have developed a regional model to estimate NPP based on remote sensing data. The estimation of NPP with remote sensing was implemented through the transformation relationship between NPP, photosynthetic active radiation (PAR), and organic matter transformed by plants (Potter et al. 1993; Goetz and Prince 1996, 1998, 1999). According to fraction of photosynthetic active radiation (FPAR) and PAR, NPP was calculated as follows:

$$NPP = \sum_{t} [FPAR_t \times PAR_t \times \varepsilon_g \times (1 - R)]$$

where $\mathrm{FPAR_t}$ is the proportion of photosynthetic active radiation absorbed by plants, changing linearly with the Normalized Difference Vegetation Index (NDVI) obtained by remote sensing. $\mathrm{PAR_t}$ is PAR during time t. ε_g is the transformation ratio of PAR absorbed by vegetation (i.e., utilization efficiency of absorbed PAR). It was calculated according to climatic factors and moisture conditions. R is the consumption coefficient by plant autotrophy respiration (Goetz and Prince 1998, 1999). ε_g can be expressed as follows:

$$\varepsilon_g = \varepsilon \times \varepsilon^* = \varepsilon_T \times \varepsilon_V \times \varepsilon_W \times \varepsilon^*$$

where ε is the environmental stress coefficient; ε^* is the maximum efficiency for solar energy utilization of plants; ε_T is the influence coefficient of air temperature on plant growth; ε_V is the influence coefficient of vapor pressure deficit (VPD) on plant growth; and ε_W is the influence coefficient of water stress.[4]

3.3.3 Parameters Acquisition

Spectral mixture analysis (SMA) is a method of unmixing sub-pixels. The spectral signature of mixed pixels was viewed as the mixture of the spectral signature of various pure ground objects (i.e., a mixed pixel is made up of many pure ground objects). The region is dominated by xerophytes, super-xerophytes, desert shrub, and halophytes. Using the method of unmixing mixed pixels, the spatial structure of the heterogeneous vegetation canopy was acquired and then PV, NPV, bare soil, and water body/ice–snow components could be identified. In multispectral images, the spectral signature of mixed pixels of each band consists of sub-pixels or end-members of pure ground objects. In the linear mixed model, the reflectance of each spectral band in a single pixel is expressed as a linear combination of respective abundance in end-member components with its reflectance (Asner and Lobell 2000; Asner and Heidebrecht 2002; Asner et al. 2004). Therefore, the reflectance ($\rho(\lambda)_{\mathrm{pixel}}$) of pixels in band No.λ can be expressed as follows:

$$\rho(\lambda)_{pixel} = \sum_{m=1}^{n} [C_m \times \rho_m(\lambda)] = [C_{PV} \times \rho_{PV}(\lambda) + C_{soil} \times \rho_{soil}(\lambda) + C_{NPV} \times \rho_{NPV}(\lambda) + C_W \times \rho_W(\lambda)]\varphi$$

where $\rho_m(\lambda)$ is the reflectance of every end-member m in wave band No.λ; C_m is the abundance or proportion of each end-member; and φ is the residual error. Channels 1, 2, and 3 of NOAA/AVHRR, corrected by atmospheric radiation in the growth period, were decomposed with the SMA method. The end-member was decided by field investigation and thematic mapper (TM) image characteristics. In this way, the pixel resolution error was effectively reduced. Vegetation indices are susceptible to atmosphere and soil conditions, especially in sparse coverage areas. In addition, the photosynthesis status of sparse desert vegetation cannot be detected. Therefore, LUE could be estimated with mixed spectral separation algorithms of photosynthetic tissue of vegetation and structure distribution, which considered xerophytic, super-xerophytic, shrub, sub-shrub, phylloclade, and other vegetation characteristics in the study area. The maximum solar energy utilization efficiency ε^* is calculated as follows:

$$\varepsilon^* = C_{PV} \times \sigma$$

where C_{PV} is the vegetation component of photosynthesis after unmixing mixed pixels and σ is the maximum efficiency for solar energy utilization of vegetation. Because the σ value depends on different photosynthesis modes, 1.00 g of carbon per mega joule (gC/MJ) was used in this chapter (Running et al. 1996; Goetz and Prince 1998, 1999).

3.3.4 Performance of the Model

Using ArcGIS 9.0 remote sensing software as the platform, the extensive NPP-GPEM module of multi-scale terrestrial ecosystem productivity was estimated using remote sensing data. Arc/INFO provides Arc Macro Language (AML). AML and the application programs can be developed by the user. AML is a target-oriented graphic model language. The hierarchical organizational structure is convenient for the function call of input data by the ARC IMAGINE image process and GIS. Meanwhile, the open-type AML code integration is convenient for adjusting model parameters, improving modules, and extending function (Chen et al. 2001). With the comprehensive utilization of climatic data from weather stations and environmental parameters, the construction idea of the CASA remote sensing model can improve the flexibility of the model and reduce over-dependence on single climatic data or remote sensing data. A supporting platform is provided for the future application of other remote sensing data as well as a foundation for using multi-source remote sensing data.

3.4 Results

3.4.1 Validation

In order to assess the accuracy of simulation results with the NPP-GPEM model, the measured data of 73 sampling points were collected to validate the estimated annual average results over 20 years (1981–2000). The data is from the Chinese Earth System Science Data-Sharing Network, as well as from field-measured data (Running et al. 2000). A comparison between predicted NPP and observed NPP is shown in Fig. 3.3. The correlation coefficient between the predicted value and the measured value was 0.86 ($n = 73$, $P < 0.001$). The simulated value was slightly larger than the measured one. The reliability of the model was proven to be high, and the spatial distribution of NPP in the Xinjiang terrestrial ecosystem over 1981–2000 was made with the model.

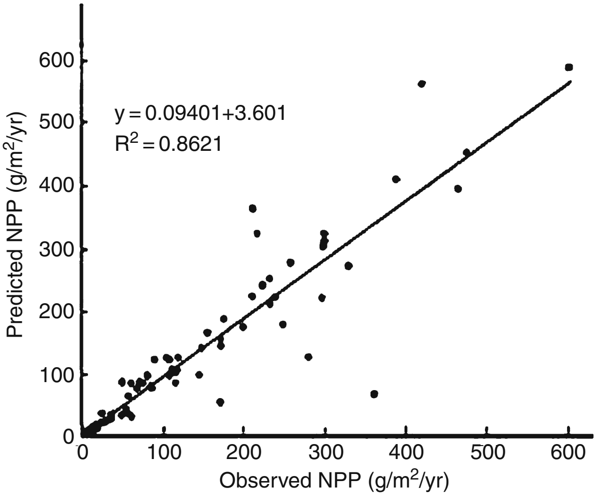


Fig. 3.3 Scatter plot between observed NPP and predicted NPP

3.4.2 Spatial Distribution of NPP in Xinjiang's Terrestrial Ecosystem

Because Xinjiang is far from oceans and is surrounded by mountains, precipitation is low and the air temperature changes drastically. Xinjiang's typical climate can be divided into several types based on geographical position. The northern part has an arid, temperate continental climate, whereas the south exhibits an arid-warm, temperate continental climate. Furthermore, the natural vegetation pattern also changes with latitude, longitude, and altitude, which is called three-dimension zonality.

The results show that the total amount of NPP in Xinjiang's terrestrial ecosystem is 0.149–0.195 gigatons of carbon per year (Gt C/yr) over 1981–2000, and the average is 0.175 Gt C/yr, accounting for about 4.87–5.4% of the total amount of NPP in China (the total amount of NPP was reported as 3.06–3.61 Gt C) (Cao et al. 2002; Tao et al. 2003). The coefficient of variation (CV) of NPP was 0.104%, the standard deviation was 0.000182 Gt C, and the range of variation was about 0.046 Gt C, which accounted for 26.3% of the mean value over 20 years. The average unit area NPP was minimum in desert areas (0.0 g of carbon per meter square per year, or gC/m^2/yr) and maximum in oasis farmland (328.76 gC/m^2/yr); the mean unit area NPP in Xinjiang was 101.33 gC/m^2/yr. The NPP showed an obvious increasing trend over 20 years (slope = 0.00142 Gt C/yr, $P<0.001$) (Fig. 3.4). The total amount of NPP was large in 1988, 1993, 1994, 1998, and 1999 and small in 1982, 1983, 1985, and 1986. The maximum was 0.195 Gt C in 1993 and 1994 and the minimum was 0.155 Gt C and 0.149 Gt C in 1983 and 1985, respectively. Although the area of Xinjiang accounts for 17% of the area of China, the total amount of NPP in Xinjiang was only 4.87 to 5.4% of the country's total. NPP has a certain spatial distribution based on the environmental conditions. According to the average NPP

Fig. 3.4 Annual variations of NPP from 1980 to 2000 in Xinjiang

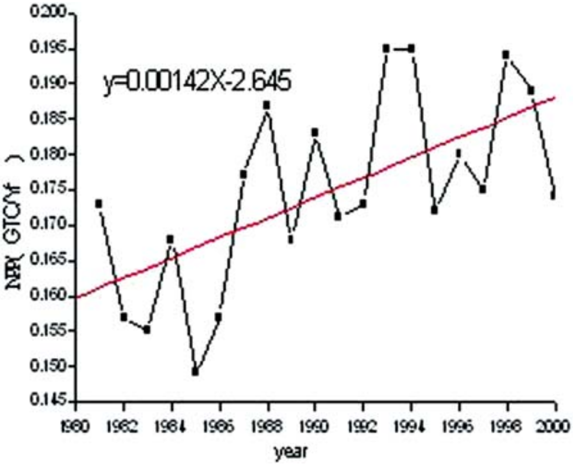
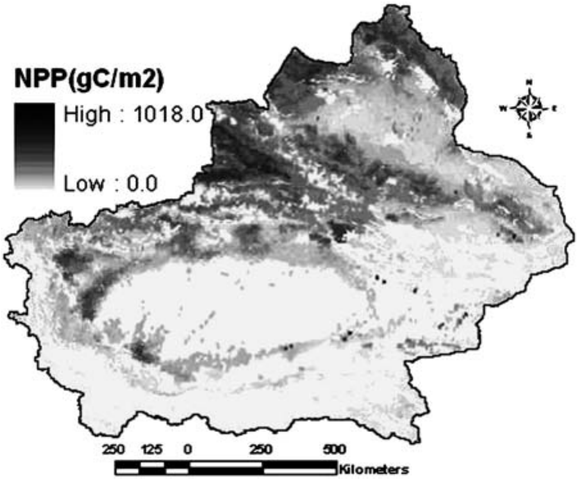


Fig. 3.5 Spatial distribution of unit area NPP in 1981



over 20 years, the spatial distribution of NPP in Xinjiang's terrestrial ecosystem shows NPP is higher in the north than it is in the south, with a gradually increasing trend from the southeast to the northwest (Figs. 3.5 and 3.6).

3.4.3 Spatial–Temporal Pattern Variance of NPP in Xinjiang's Terrestrial Ecosystem

The mean unit area NPP over 20 years was compared with the 1981 baseline (Figs. 3.7 and 3.8). Figure 3.7 shows the variance rate of NPP from 1982 to 2000, indicating the NPP of most areas in Xinjiang increased over the 20 years. NPP increased by as much as 18.35% in the east part of the Altay Mountains area. The increase rates amount to 20.04% and 16.41% in the north-face slope of the Karakorum Mountains and the Pamir Plateau areas, respectively.

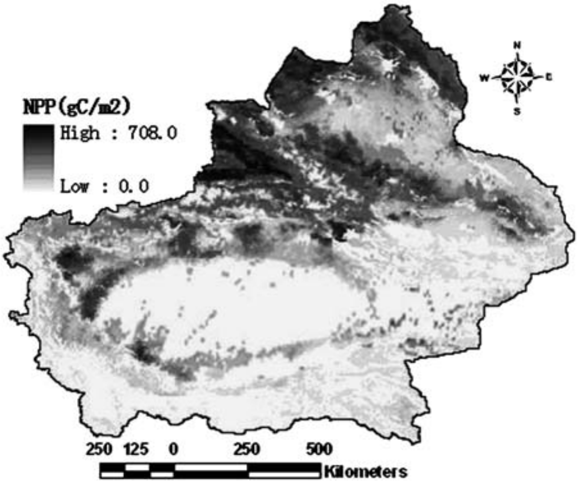


Fig. 3.6 Spatial distribution of mean unit area NPP from 1982 to 2000

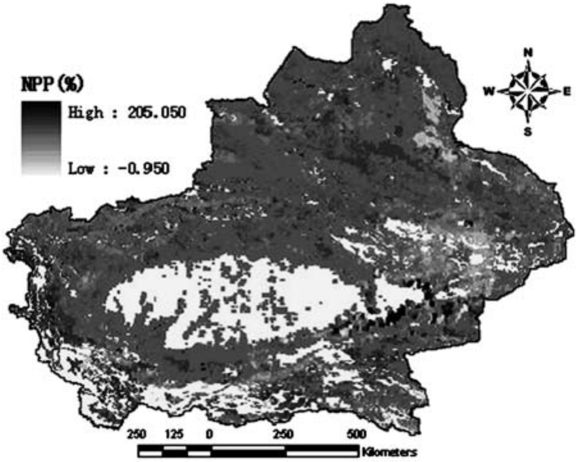


Fig. 3.7 Spatial distribution of variance rate of NPP from 1982 to 2000 compared with the baseline (1981)

Figure 3.8 shows that the regions with increased NPP were mainly in north Xinjiang, including the west part of the Altay Mountains area, the south Altay Mountains piedmont plain, the Shawuer Mountains area, and the west part of the Tian Shan north piedmont plain.[5]

3.4.4 Interannual and Intergenerational Spatial–Temporal Pattern of NPP in Xinjiang

Figure 3.9 shows the spatial–temporal pattern of NPP in five-year intervals. According to the comparison of NPP between 1996–2000 and 1980–1985, the NPP increased in most areas of Xinjiang. Some areas had a decrease in NPP, including the north part of Junggar Basin, Gurbantonggut Desert, Lop Nor, and the east plain

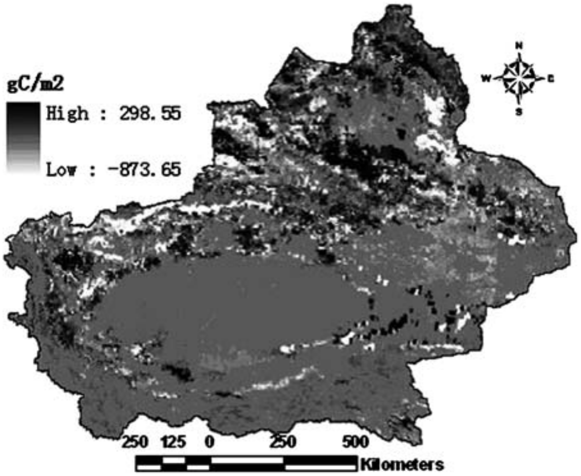


Fig. 3.8 Spatial distribution of absolute variance of NPP from 1982 to 2000 compared with the baseline (1981)

at the north-face slope of the Kunlun Mountains.[6] NPP increased in most areas of Xinjiang from the 1980s to the 1990s, but decreased in the north part of Junggar Basin, Gurbantonggut Desert, Lop Nor, and the east piedmont plain at the north-face slope of the Kunlun Mountains. The unit area NPP decrements are 1.95 gC/m^2, 0.55 gC/m^2, 2.71 gC/m^2, and 2.63 gC/m^2, respectively, over 10 years, which was consistent with the change over 20 years.[7]

When NPP variation at five-year intervals was compared for the Xinjiang terrestrial ecosystem, six trends emerged (Table 3.1).

1. NPP increased in 18 areas for three sequential five-year time intervals (from 1981 to 1995). The west part of the piedmont plain at the Tian Shan north-face slope and the Kashi-Shache Delta had the largest NPP increase in north Xinjiang and south Xinjiang, respectively.
2. NPP increased in 13 areas for two sequential five-year intervals (from 1981 to 1990) and decreased in the third five-year interval (1991–1995). The north Junggar Basin saw the largest variation in north Xinjiang, and the Hami Basin had the largest variation in south Xinjiang.
3. NPP increased in three areas—all in south Xinjiang—in the first and the last five-year time intervals (1981–1985 and 1996–2000) and decreased in the other five-year time intervals (1986–1990 and 1991–1995).
4. NPP decreased in the first two five-year time intervals (1981–1985 and 1986–1990) and increased in the last five-year time interval (1996–2000). The east plain at the north-face slope of Kunlun Mountains had an NPP decrease in the first two five-year intervals and an increase in the last five-year time interval.
5. NPP increased in the first five-year time interval (1981–1985) and decreased in the following two time intervals (1986–1990 and 1991–1996). This occurred in the piedmont plain of the south-face slope of the Altay Mountains.
6. NPP decreased in the first three five-year time intervals in Lop Nor in south Xinjiang.

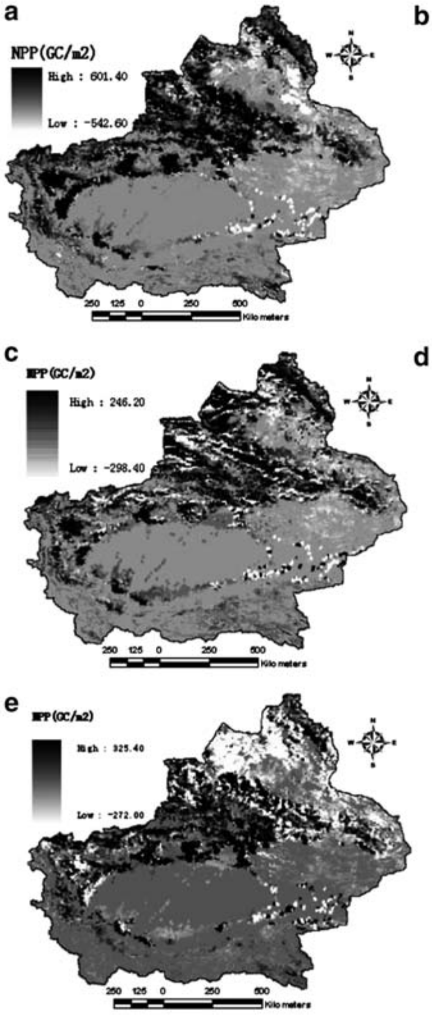


Fig. 3.9 A comparison of variations of estimated NPP at five-year time intervals (**A**: 1981–1985 to 1996–2000; **B**: 1980s to 1990s; **C**: 1981–1985 to 1986–1990, **D**: 1986–1990 to 1991–1995; **E**: 1991–1995 to1996–2000)

In terms of seasonal variation, NPP generally increased in spring, summer, and autumn (Fig. 3.10). The largest increase appeared in spring (March–May), while the smallest occurred in summer (June–August). NPP decreased in winter.

3.5 Methodological Analysis

The vegetation canopy structure was analyzed in terms of the particular climate–vegetation characteristics in the arid region. The objective was to identify the functional difference in vegetation and disturbance of the environmental

Table 3.1 The changes of NPP with sequential 5- and 10-year intervals in Xinjiang

		5 Yr	5 Yr	5 Yr	5 Yr		10 Yr
Code	Regions	1981–1985 (gC/m^2)	1986–1990 (gC/m^2)	1991–1995 (gC/m^2)	1996–2000 (gC/m^2)	1981–1990 (gC/m^2)	1991–2000 (gC/m^2)
IA1	Western Altay Mountain Area	302.4460	320.4611	323.0892	330.7825	311.4536	326.9359
IB1	South Altay Mountain piedmont plain	325.8738	366.8245	361.5759	361.1889	346.3492	361.3824
IB2	E′erqisi He and Wulun He	157.4631	169.8567	170.5995	162.9125	163.6599	166.7560
IA3	Shawuer Mountain Area	227.8137	236.6489	266.5876	237.4473	232.2313	252.0174
IA4	Tacheng Basin	358.2097	399.1426	409.4624	385.7055	378.6762	397.5839
IA5	Tuoli Hill	210.0645	242.7108	259.5217	229.5337	226.3876	244.5277
IB3	Northern Junggar Basin	118.1712	122.5048	130.4591	106.3226	120.3380	118.3909
IA2	Eastern Altay Mountain Area	157.5697	168.7977	176.4953	163.1110	163.1837	169.8032
IB4	Gurbantonggut Desert	72.3870	72.6981	75.0091	68.9848	72.5425	71.9969
IC2	Boertala Valley	261.2036	293.4143	294.0589	296.7651	277.3090	295.4120
IC1	Yili Valley	360.3127	385.1087	391.3353	401.0011	372.7107	396.1682
IB5	West part of Tian Shan north piedmont plain	221.8028	249.2508	267.2472	280.3918	235.5268	273.8195
IC3	West part of piedmont plain in north-face slope of Tian Shan	192.1231	203.2029	215.1797	220.5403	197.6630	217.8600
IC5	Balikun-Sant. Basin	95.1197	98.5438	106.0418	98.9795	96.8317	102.5106
IB6	East part of Tian Shan north piedmont plain	223.2614	239.5839	259.7422	260.9443	231.4226	260.3433
IC4	Eastern piedmont plain in north-face slope of Tian Shan	237.1581	257.8445	265.1126	268.7324	247.5013	266.9225
IIA4	Youledus Basin	198.5600	220.8364	231.8834	243.5223	209.6982	237.7028
IC6	Yiwu-Naomaohu Basin	74.6997	77.0780	84.4336	77.2075	75.8888	80.8206
IIA2	Turpan Basin	65.4694	70.1068	70.9204	69.8368	67.7881	70.3786
IIA7	South-face slope at Tian Shan Mountains and Tuoshigan Valley	144.0546	156.7732	161.2082	173.8838	150.4139	167.5460
IIA6	Baicheng Basin	150.4093	158.6648	161.6072	170.3229	154.5370	165.9651
IIA3	Yanqi Basin	167.6010	182.8473	179.2263	193.2013	175.2241	186.2138
IIA5	Middle part of south-face slope of Tian Shan Mountains	183.9120	212.0408	198.6761	214.5302	197.9764	206.6031

Table 3.1 (continued)

		5 Yr	5 Yr	5 Yr	5 Yr		10 Yr
Code	Regions	1981–1985 (gC/m^2)	1986–1990 (gC/m^2)	1991–1995 (gC/m^2)	1996–2000 (gC/m^2)	1981–1990 (gC/m^2)	1991–2000 (gC/m^2)
IIA1	Hami Basin	53.4888	56.6635	58.2697	56.7872	55.0761	57.5284
IIB1	Western piedmont plain at Tian Shan south-face slope	151.5573	167.9232	179.5903	197.7900	159.7402	188.6902
IIB2	Eastern piedmont plain at Tian Shan south-face slope	115.6340	123.6334	122.8417	135.4592	119.6337	129.1505
IIA8	Keping-Haerpo Basin	100.3628	113.3999	116.3604	121.3648	106.8814	118.8626
IIC1	Pamir Plateau	32.0491	39.3233	43.5716	44.8881	35.6862	44.2298
IIB3	Kashi-Shache Delta	152.1617	167.6303	197.9927	204.9616	159.8960	201.4771
IIB7	Taklimakan Desert	24.9101	26.8053	27.6751	27.3373	25.8577	27.5062
IIB6	Lop-nor	27.9516	26.0973	25.6699	22.9486	27.0245	24.3092
IIC2	North-face slope of Karakorum Mountain	32.7296	39.2679	43.7418	46.3254	35.9988	45.0336
IIB5	East piedmont plain at north-face slope of Kunlun Mountains	35.5452	34.6212	32.1655	32.7480	35.0832	32.4568
IIB4	West piedmont plain at north-face slope of Kunlun Mountains	69.3254	77.2512	79.7786	84.6925	73.2883	82.2356
IIC5	Aerhchin Mountains	18.6642	21.4770	22.9636	23.1021	20.0706	23.0329
IIC3	Middle part of Kunlun Mountains and Akesaiqin Basin	6.7868	9.0874	10.1345	10.0748	7.9371	10.1047
IIC4	Middle part of Kunlun Mountains	2.7498	3.6349	5.3530	5.3628	3.1923	5.3579

background. An NPP-GPEM model suited to the region was built based on the principle of vegetation absorbing and utilizing photosynthetic active radiation, combined with remote sensing technology.

The NPP-GPEM model was validated with measured data of Xinjiang's terrestrial ecosystem. NOAA/AVHRR satellite remote sensing data and the ground meteorological data (from 1981 to 2000) were used to estimate annual NPP over 20 years. The distribution diagram of monthly and annual NPP with 1 km resolution was obtained. Based on the analysis of NPP spatial distribution patterns, the model with physiological characteristic of vegetation in arid regions gave rational results.

Although the validated results indicated that the simulating effects were relatively reasonable, the 73 sampling points collected mainly from desert and grassland

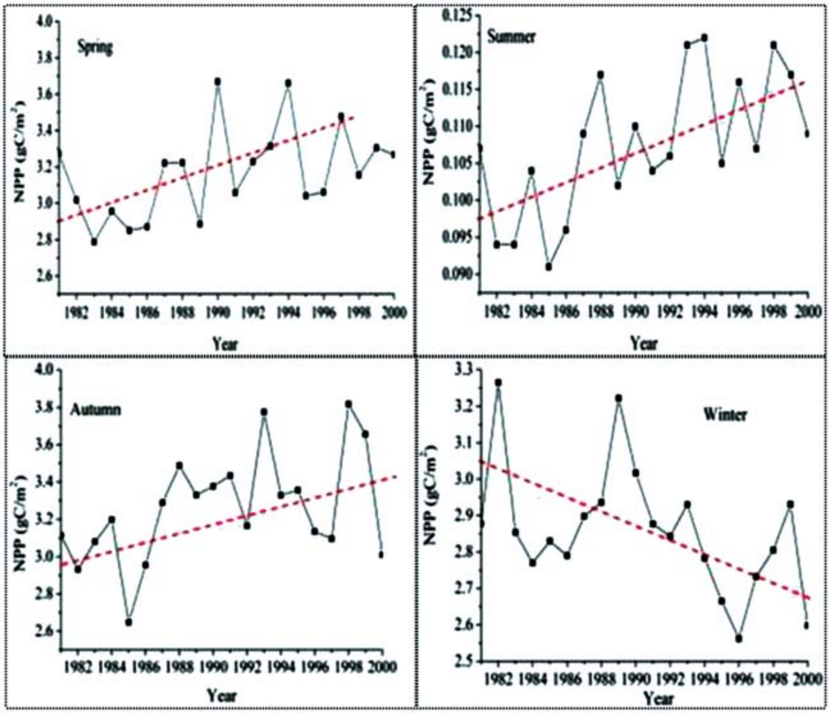


Fig. 3.10 Interannual variation of estimated seasonal NPP

zones could not represent all ecosystem types in the region. Future efforts should include strengthening field investigations in different ecosystem types to reflect the heterogeneity and difference in regional ecological functions. At the same time, the field investigations will help validate the suitability of the GLO-PEM, CEVAS, and CASA models in the study area.

With the model performance of monthly sequential remote sensing data, the disturbance, increment, or subduction of surface NPP imposed by human activities—farmland management, forest fire control, plant destruction and restoration, and forestation and deforestation—could be directly identified. In addition, the impact of climatic changes on vegetation photosynthesis and carbon absorption could be detected.

Notes

1. The desert shrub, for example.
2. NOAA/AVHRR: National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer; SPOT/VEGETATION: Systeme Probatoire d'Observation de la Terrestrial; and EOS/MODIS: Earth Observing Satellites/Moderate Resolution Imaging Spectroradiometer.

3. This study is supported by Xinjiang Higher Education Project (XJEDU2005I06), Dr. Fund of Xinjiang University (BS050110).
4. A detailed calculation of these coefficients has been described in relevant articles about CASA and GLO-PEM models (Philip and Dar 2003; Steven et al. 1983; Tucker et al. 1983; Prince and Tucker 1986; Colltaz and Ball 1991; Zhou and Zhang 1996; Leemans and Camer 1991; Chen et al. 2001).
5. The absolute amount of increase is 10.52 gC/m^2, 19.43 gC/m^2, 9.44 gC/m^2, and 17.29 gC/m^2, respectively. The regions with NPP increases in south Xinjiang were mainly in the Yanqi Basin, the middle part of the south-face slope of the Tian Shan Mountains, the west part of the piedmont plain at the Tian Shan south-face slope, and the north-face slope of the Karakorum Mountains. The absolute amount of NPP increases were 5.0 gC/m^2, 5.0 gC/m^2, 6.03 gC/m^2, and 5.68 gC/m^2, respectively. The increase was as much as one-fourth of the maximum increase in north Xinjiang. Although most areas in north Xinjiang had an increasing trend in NPP, there were some areas with NPP decreases, such as the north part of the Junggar Basin and the Yili Valley, which showed a drop of 0–0.44 gC/m^2. South Xinjiang, Yiwu-Naomaohu Basin, Turpan Basin, the south-face slope at the Tian Shan Mountains and Tuoshigan Valley, Baicheng Basin, Hami Basin, Keping-Haerpo Basin, Lop Nor, and the east piedmont plain at the north-face slope of the Kunlun Mountains had a certain NPP decrease. Among them, the largest decrement appeared at the south-face slope of the Tian Shan Mountains, Tuoshigan Valley, and Baicheng Basin. The absolute increases were between 0 and 5.0 gC/m^2 for other areas in Xinjiang. The increase rate is high in the east part of the Altay Mountains area, the north-face slope of the Karakorum Mountains, and the Pamir Plateau. The absolute increases in the three areas were between about 3 and 6 gC/m^2; the largest absolute increases took place in the west part of the Altay Mountains area, the piedmont plain at the south-face slope of the Altay Mountains, the Shawuer Mountains area, and the west part of the piedmont plain at the Tian Shan north-face slope. The increase rate of those areas was between 3 and 7.5%. In addition, four areas showed a negative absolute variation: Yili Valley, Baicheng Basin, Lop Nor, and the east piedmont plain at the north-face slope of the Kunlun Mountains. The NPP increase for the entire Kunlun Mountains area was as high as 6.82%. Some areas, however, such as Turpan Basin, Hami Basin, the south part of the Tian Shan Mountains, Tuoshigan Valley, and Keping-Haerpo Basin in south Xinjiang showed negative growth rates. The Turpan Basin area saw a rapid NPP decrease. Some areas in north Xinjiang also showed negative growth rates, including the north part of Junggar Basin, Gurbantonggut Desert, Boertala Valley, Balikun-Santanghu Basin, and Yiwu-Naomaohu Basin. The growth rate of the five areas was –0.61%, –1.86%, –0.48%, –1.58%, and –1.92%, respectively. Yiwu-Naomaohu Basin showed a rapid NPP decrease in northern Xinjiang. However, the Altay Mountains region and the north-face slope of the Tian Shan Mountains area showed an increase of NPP. In addition, the NPP increased by 5–10% in some areas: the south-face slope of the Altay Mountains piedmont plain, Tuoli Hill, the west part of the piedmont plain in the north-face slope of the Tian Shan, Lop Nor, the east part of the plain at the north-face slope of the Kunlun Mountains, the middle part of the Kunlun Mountains, and Akesaiqin Basin. The NPP of other areas increased by 0–5%. As a whole, the areas with an obvious NPP decrease in Xinjiang were mainly Yiwu-Naomaohu Basin and Hami Basin in south Xinjiang (about 7–10%).
6. The decreased amounts of unit area NPP over 20 years were 11.85 gC/m^2, 3.40 gC/m^2, 5.00 gC/m^2, and 2.80 gC/m^2, respectively. The maximum decreased amount appeared in the north part of Junggar Basin. Other areas such as the west part of Tian Shan north piedmont plain, Youledus Basin, the west plain at the south-face slope of foot of the Tian Shan Mountains and Kashi-Shache Delta showed a relatively high NPP increment over 20 years; the absolute increments were 58.59 gC/m^2, 45.00 gC/m^2, 46.23 gC/m^2, and 52.80 gC/m^2, respectively. The west part of the piedmont plain at the north-face slope Tian Shan had the largest increment in north Xinjiang, and Kashi-Shache Delta showed the largest in south Xinjiang. Boertala Valley, Yili Valley, the piedmont plain of south-face slope of Altay Mountains, the east part of Tian Shan north-face slope piedmont plain, the east part of the Tian Shan north-face slope, and

the middle part of Tian Shan south-face slope increased in NPP over 20 years. Their absolute increments were 35.56 gC/m^2, 40.69 gC/m^2, 35.32 gC/m^2, 37.68 gC/m^2, 31.57 gC/m^2, and 30.62 gC/m^2, respectively. The west part of Altay Mountains Area, Tacheng Basin, Tuoli Hill, the west part of Tian Shan north-face slope, the south part of the Tian Shan Mountains and Tuoshigan Valley, Baicheng Basin, Yanqi Basin, the east piedmont plain at south-face slope of the foot of the Tian Shan, Keping-Haerpo Basin, and the west plain at the north-face slope of the Kunlun Mountains showed an absolute increment between 15 and 30 gC/m^2 over 20 years. Generally, the average unit area increment (from 1980 to 2000) in all of Xinjiang was 11.23 gC/m^2. The total increment of NPP was 0.018 Gt C/yr during the period.

7. Lop Nor showed the largest decrement. Yili Valley, the west part of the piedmont plain at the Tian Shan north-face slope, the west part of the Tian Shan north-face slope, the east part of the piedmont plain at the Tian Shan north-face slope, Youledus Basin, the west piedmont plain at the south-face slope of the Tian Shan and Kashi-Shache Delta showed a relatively large increment from the 1980s to the 1990s, with an absolute increment of 23.46 gC/m^2, 38.29 gC/m^2, 20.20 gC/m^2, 28.92 gC/m^2, 28.00 gC/m^2, 28.95 gC/m^2, and 41.58 gC/m^2, respectively; the west part of the piedmont plain at the Tian Shan north-face slope had the largest increment in north Xinjiang, and Kashi-Shache Delta had the largest increase in south Xinjiang. NPP rose 0–20 gC/m^2 in other regions during the 10 years, and the mean value was about 10 gC/m^2.

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Chapter 4
The Recent Evolution of the Oasis Environment in the Taklimakan Desert, China

Yalikun Tashi, Philippe C. Chamard, Marie-Françoise Courel, Tashpolat Tiyip, Yiliminuer Tuerxun, and Sam Drake

Abstract Numerous natural and anthropogenic factors have caused soil salinization, land surface degradation, and desertification in Keriya County in China's Xinjiang region. Information from multi-temporal remotely sensed data such as the Soil Salinity Index (SSI) has contributed significantly to an understanding of these environmental changes. The approach to calculating SSI is based on the spectral bands of Landsat Thematic Mapper (TM) or Enhanced Thematic Mapper Plus (ETM+). A soil salinity map of the Keriya County area was produced from Landsat ETM+ images, with an overall accuracy of 72.73% and kappa coefficient of 0.6689. The analysis of the recent evolution of the oasis of Keriya County was carried out by coupling climatic and socioeconomic data with information derived from multi-temporal remotely sensed data such as the SSI, Normalized Difference Vegetation Index (NDVI), and different land use classes. Such analysis appeared to be very useful in identifying and monitoring changes occurring in the oasis ecosystem and for understanding the consequences of human-induced land degradation processes.

Keywords Ecosystem degradation · Keriya · Oasis · Remote sensing · Xinjiang

4.1 The Xinjiang Region: An Overview

The Xinjiang Uygur Autonomous Region of the People's Republic of China covers 1,646,800 km^2, or 16% of Chinese territory. This huge region is also one of the least densely populated provinces of China. Indeed, the November 2000 census shows that its 19.25 million residents represent only 1.5% of China's total population (Statistical Office of Xinjiang 2006).

Xinjiang is divided into two basins by the Tian Shan, one of the largest mountain ranges in the world: the Junggar Basin (380,000 km^2) to the north and the Tarim

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G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
DOI 10.1007/978-90-481-2776-4_4, © Springer Science+Business Media B.V. 2010

Basin (530,000 km^2) to the south (Fig. 4.1). The Junggar Basin is situated between the Tian Shan and Altai mountains. Unlike the Tarim Basin, it opens to the northwest through a series of large gaps in the encircling ranges. Because it is exposed in this way to the climatic influences of Siberia, the Junggar Basin has colder temperatures and more precipitation than the enclosed Tarim Basin. The principal cities in the Junggar Basin are Urumqi, Shehezi, Ghulja, Karamay, Altay, and Changji, and the basin holds China's second largest desert, the Gurbantünggüt.

The Tarim Basin is bordered by the Tian Shan, Pamir, and Kunlun mountains and stretches 1,000 km from west to east and 500 km from north to south. The Taklimakan Desert sits in the center of the basin and covers 337,000 km^2. Oasis cities, including Korla, Kuqa, Aksu, Kashgar, Yarkand, Hotan, and Keriya, are distributed around the desert.

Far from the ocean and enclosed by high mountains, Xinjiang has a dry, continental climate with little rainfall (Xia 1993). Recorded annual rainfall accumulations range from 100 to 200 mm in the Junggar Basin and from 25 to 50 mm in the Tarim Basin. Turpan, a county-level city in Turpan Prefecture in eastern Xinjiang, has seen rainfall totals of as little as 3.9 mm. Adding to the aridity, the potential evapotranspiration values are very high because of the intensity of solar radiation and because the sun generally shines as long as 2,500–3,500 hours per year in the region. Annual evaporation rates range from 2,000 to 3,000 mm in the Tarim Basin and from 1,500 to 2,000 mm in the Junggar Basin. Average July temperatures are between 20 and 24°C, with Turpan recording 47°C. Average January temperatures for the region vary between –8 and –20°C. Again, Turpan holds the temperature record: –51.5°C. Under such conditions, the world aridity map has classified most of Xinjiang as arid or hyper-arid (UNESCO 1997).

Despite the arid climate, water resources are rich. The enormous mass of ice stored in the surrounding high mountains supplies the region with water and ensures the existence of the desert oases. An inventory has identified an estimated 23,000 glaciers within Chinese territory (Shi et al. 1989). The ice-covered surface approaches 29,000 km^2 and the volume of ice is about 29,000 km^3. The annual melt water volume is estimated to be 2.4 billion m^3. For its part, the Tarim Basin collects 69% of this water as snowmelt from the Tian Shan and Kunlun mountains, which respectively represent 34.5% and 31% of the total ice in China (Shi et al. 1989). Such advantages explain the long history of the oases in Xinjiang. However, observations made by geographers and local authorities have shown that the ecological environment of Xinjiang has been degraded since the beginning of the twentieth century due to climatic conditions and human activities (Wang 1998; Xia 1993; Coque and Gentelle 1991).

Satellite imagery has contributed significantly to an understanding of environmental changes caused by natural processes and human activities (Goetz et al. 2000; Prince 1991; Courel et al. 2001). It provides objective criteria for comparing environmental changes in different areas, or monitoring change in the same area over time, from multi-temporal images.

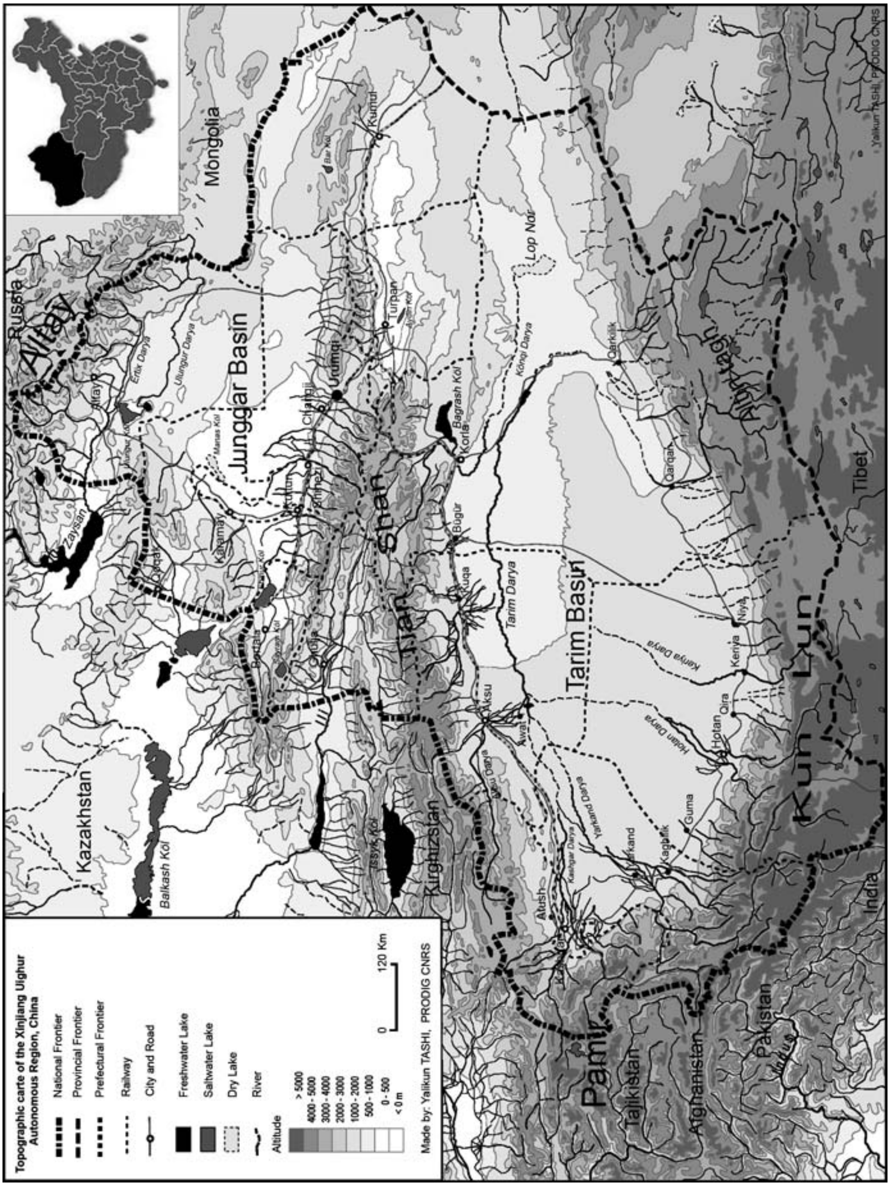

Fig. 4.1 Topographic map of Xinjiang

4.2 Environmental Degradation in Xinjiang

The oases of Xinjiang are fragile and threatened more by agricultural and pastoral activities of the rapidly growing population than by current climatic conditions. This idea is initially suggested by archaeology; cities of the Han Dynasty (206 BC–220 AD) and Tang Dynasty (618–907 AD) had been built within the Taklimakan Desert, on the edges of the valleys of inter-dune rivers whose waters were much more abundant than they are today (Gentelle 1992). Extensive animal husbandry was practiced around these cities, rain was more abundant, and the climate was slightly warmer during the two dynasties than it is today. These conditions consequently were more favorable to snow and ice melts at the end of winter, and to the best hydrological functioning of the rivers. The oasis of Loulan had occupied several hundred hectares 1,700–2,000 years ago. Today, it has disappeared as a result of changes to the beds of the Kongqi and Tarim rivers. Other oases also disappeared from lack of water. Sir Marc Aurel Stein, a Hungarian archaeologist who made four major expeditions to Central Asia in 1900, 1906–1908, 1913–1916, and 1930, marked a number of them on his map, reprinted by the Army Map Service of the United States after World War II (Stein 1907). A few hundred years ago, the Qira and Yengsar oases were two to three times larger than they are today. This can be explained by bad irrigation management, which led to a rise in groundwater levels, a proliferation of salt crusts on the surface, a decline in agricultural production, and the eventual departure of farmers.

More than 90% of the surface of Xinjiang is covered by mountain ranges, deserts, and semi-deserts. Only 4% of the region's area is favorable to settled agricultural activities. In the last five decades, its population has quadrupled, with migration playing a key role (Courbage 2000). Between 1953 and 1964, the population immigrating to Xinjiang from other provinces of China spiked from 330,000 to 2.3 million, with an average annual growth rate of almost 20%, and immigration doubled between 1964 and 1982. It is understandable, therefore, why the demographic pressure on the oasis environment is so strong. Some oases have a population density of more than 825 people per square kilometer.

Population growth, the extension of cultivated area, over-exploitation of resources, and the careless use of water have resulted in serious problems of soil salinization, land surface degradation, and desertification (see Chapters 1–3). According to a report from the Department of Environmental Protection of Xinjiang, as reported by *Xinjiang Daily* newspaper in June 1998, desertification has progressed in 53 of 87 counties in the province, and many lakes are now drying up, especially along the Tarim River. The Tarim is the main river in Xinjiang (2,179 km); it runs on the southern slope of the Tian Shan and irrigates a major part of the Korla region. It is reported that the volume of water transported by the lower reach of the river fell to 289 million m^3 in 1998, compared with 1.1 billion in the 1960s (Xie and Mao 1989). Moreover, the wooded area in the watershed shrank by more than 110,000 mu (1 mu = 666 m^2).

Ecological degradation affects not only the oases. A report quoted by the *People's Daily* newspaper in January 2001 estimated that 80% of the 57 million hectares

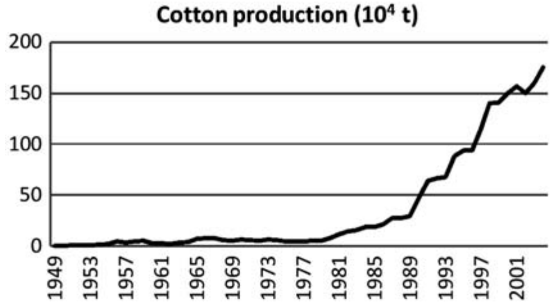

Fig. 4.2 Cotton production of Xinjiang

(ha) of natural pastures in Xinjiang has been degrading at a rate of 0.5% per year since 1980. Since that year, more than 7 million ha has been used for agriculture or development, and human activities have destroyed more than 266,700 ha per year.

In a particularly fragile environment like that of Xinjiang, which is subject to desertification and water shortages, the policy of massive deforestation is likely to have disastrous effects. The transitional belts between deserts and cultivated areas are precisely the zones that are ensuring the preservation of the cultivated areas. Turning them into crop lands likely will disrupt the fragile natural balance of the oasis ecosystem.

The introduction of obligatory cotton cultivation has been a major policy of the Chinese government since the early 1990s (Fig. 4.2). The description of the development strategy for Xinjiang can be summed up by two colors: black, for industry and oil (which was discovered in 1986), and white, for cotton and agriculture. Thus, in the 1990s, the agricultural policy implemented in Xinjiang quickly passed from a goal of self-sufficiency in grain cultivation to one of cotton cultivation. The objectives of the agricultural policy set by the Eighth Five-Year Plan (1991–1995) were to increase the production of cereals and cotton, improve productivity, and increase farmers' incomes. However, the isolation and remoteness of the oases of Xinjiang, as well as extremely reduced cultivated area per capita, put the subsistence of the farmers at the mercy of a bad harvest.

According to field investigations and interviews with farmers, extremely strict quotas of cotton production are imposed on the farmers in terms of cultivated area and output. Farmers insisted they earn no profits from cotton production due to various expenses (pesticides, fertilizers, and plastic film) and the high labor requirements involved. The farmers believed that the cash they had received from state cooperatives as payment for the sale of cotton did not allow them to pay back their investments in capital and labor. In 1915 the oasis produced only 84 tons of cotton. It produced 208 tons in 1950 and 3,414 tons in 2004 after reaching a peak of 9,683 tons in 1998.

The cotton cultivation policy is harmful to the soil because it requires large amounts of water (producing 100 kg of cotton requires 400–800 m^3 of water), and exacerbates the problem of salinization. The culture of cotton also runs counter to the principle of crop rotation, which fragile soils require. Thus, the intensive cultivation of cotton—even if it were successful for a few years—might finally exhaust

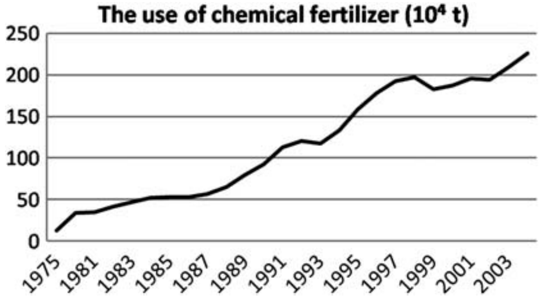

Fig. 4.3 The use of chemical fertilizers in Xinjiang

the soil. Moreover, the extensive use of fertilizers (Fig. 4.3) and pesticides pollutes rivers and groundwater and changes the ecological balance. Hence, reducing cotton cultivation and diversifying crop types would be beneficial to farmers, increasing soil productivity and crop yields and diminishing the risk of soil salinization.

Echoes of the cotton cultivation policy may be found in the former Soviet areas of Central Asia. The policies implemented by the former Soviet Union have striking similarities to policy in Xinjiang. The planners in Moscow decided to make Uzbekistan and Kazakhstan the base of cotton production across the USSR: new lands were “conquered,” hundreds of thousands of settlers were sent to the fields, and the course of two major rivers—the Amur Darya and Syr Darya—were diverted to assure the irrigation of cotton fields (Rumer 1999).

In Uzbekistan, a complete infrastructure catering to the cotton industry was developed: an irrigation network, construction of agricultural machinery, chemical industries for fertilizers and pesticides, industrial spinning mills, and textile factories. In the mid-1980s, the cotton industry accounted for 6% of Uzbekistan’s gross national product, absorbed 60% of its resources, and employed 40% of its workforce. This policy led to the notorious ecological disaster in which the Aral Sea has been steadily shrinking since the 1960s, causing soil salinization and irreparable damage to the arable land (Glantz 1998).

Accelerated destruction of the already poor vegetation cover also has been encouraging desertification (Li et al. 1989; Biswas 1980; Le Houérou 1987). From 1958 to 1978, drought, water shortages, and deforestation led to the destruction of nearly 270,000 ha of the riparian poplar forest along the Tarim River. Sand dunes pushed by the prevailing northeast wind invaded the green corridor. The steppes of tamarisk and haloxylons in flood-submerged areas, which were still luxuriant and populated by abundant fauna 100 years ago, have become small, deserted and sandy islands. In the prefecture of Hotan, or Khotan (Hetian in Chinese), south of the Tarim Basin, the forest of poplar that had occupied 120,000 ha in 1957 has been reduced to fewer than 50,000 ha today. The population of tamarisk has been devastated by the collection of firewood within a radius of about 30 km around the oases.

Obviously, there are close links between all manifestations of desertification. The degradation of vegetation cover on the land surface is the main cause of deflation and wind erosion. Ultimately, desertification is the result of the installation of an agro-pastoral system that interacts negatively with natural processes and has destroyed the fragile natural balance of the arid environments. The consequences are alarming; the desert has gained an estimated 2.8 million ha around the Tarim Basin since the first century AD, including 900,000 ha during the twentieth century (Xia 1993).

It is understandable, therefore, that the degradation of ecosystems—natural or not—is the main source of concern not only for geographers and specialists in environmental issues but also for local authorities in charge of town and rural planning.

4.3 Study Area Description and Data Collection

The oasis of Keriya County was selected as the study area because it is one of the oases in Xinjiang that has seen the most pronounced ecological and environmental changes over the past 50 years. It is located in the southern part of the Tarim Basin, on the northern piedmont of the Kunlun Mountains and in proximity to the Taklimakan Desert. The hyperarid climate of Keriya is characterized by a cold winter and a hot summer, the dryness of the air, and the scarcity of summer rains and their rapid evaporation (He et al. 2001). According to data provided by the meteorological station of Keriya County, the average annual temperature during the reference period 1974–1999 was 11.4°C, and the thermal amplitude was in the order of 30°C: –5°C in January and 26°C in July. The average minimum temperature in January is –17°C and average maximum in July is 38.2°C.

While the average annual rainfall is about 50 mm, actual amounts observed are highly variable: the meteorological station of Keriya County recorded 6.2 mm in 1985 and 114.8 mm in 1987 (Fig. 4.4). Fifty percent of the total rainfall occurs in summer (June, July, and August) and 30% in spring (March, April, and May), while fall (September, October, and November) and winter (December, January, and February) share the remaining 20% (Figs. 4.5 and 4.6). Precipitation increases with altitude on the northern slopes of the Kunlun; precipitation totals about 300 mm at about 2,000 m. These rains, while modest, contribute to the hydrological functioning of the rivers of this region, including the Keriya River—the principal water supplier

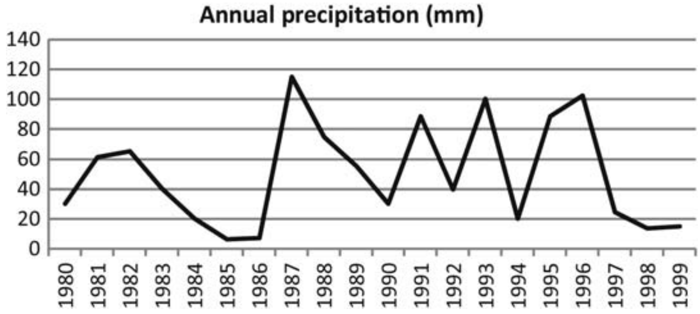

Fig. 4.4 Multi-year average precipitation in Keriya County (1980–1999)

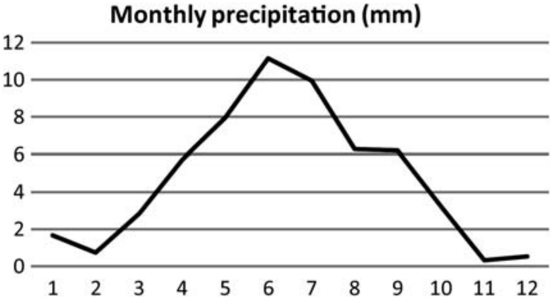

Fig. 4.5 Average monthly precipitation in Keriya County (1980–1999)

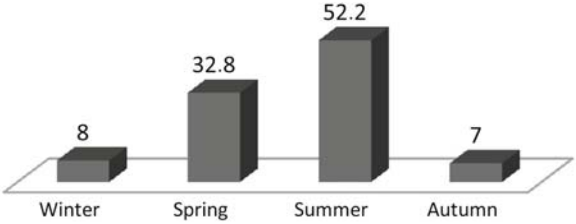

Fig. 4.6 Seasonal distribution of the total annual rainfall in Keriya County (%)

in Keriya County. The average volume of rainfall in the hydrological basin of the Keriya River (11,625 km^2) is estimated at 32.8×10^8 m^3. The volume of water transported by the river is about 7.15×10^8 m^3. This volume, which depends on melt water and rainfall, varies from one year to another: in 2001 it was 10.45×10^8 m^3 and in 1993 it totalled 4.92×10^8 m^3.

The shallow groundwater associated with the oasis is supplied by underground flows in the coarse gravel formations at the piedmont of the Kunlun and by infiltration of irrigation water circulating in unlined channels. The groundwater forms a reserve of 5×10^8 m^3. The volume of water pumped from the aquifer annually is 0.1×10^8 m^3. As potential resources, there are 430 glaciers in the Kunlun that retain 63×10^9 m^3 of water. About 2.3×10^8 m^3 of water is held in the high mountain glacial lakes, which are probably connected to the water network of the Keriya River.

The remote sensing data used in this study comprise a Landsat multispectral scanner (MSS) image acquired on June 23, 1977, a Landsat thematic mapper (TM) image acquired on October 17, 1999, and a Landsat enhanced thematic mapper plus (ETM +) image acquired on October 7, 2002.

All remote sensing imagery is inherently subject to geometric distortions (Lillesand and Kiefer 1994). Geometric corrections are intended to compensate for these distortions so that the geometric representation of the imagery will be as close as possible to the real world. Geometric registration of the imagery to a known ground coordinate system must also be performed. Georegistration and geometric correction were done on each of the selected images of the study area. The true ground coordinates of the ground control points (GCPs) were measured on a 1:50,000 scale topographic map of the study area, with the projection

Beijing_1954_GK_Zone_14. The nearest-neighbor resampling method was used because it does not alter the original image data values. The root mean square (RMS) error was controlled within one pixel for all geometrically corrected images.

After spatial subset, the image covers an area of about 4,590 km^2 located between 81°6′46″–81°59′5″ E and 36°42′50″–37°14′51″ N, comprising the major part of the oasis of Keriya County.

Two field investigations were made during October 3–15, 2002, and May 22–30, 2005. Data about environmental and socioeconomic conditions of the study area were collected, including soil salinity, vegetation cover, shallow groundwater depth, land use types, statistical reports, meteorological data, interviews with farmers, and various kinds of maps (general land use map, soil salinity map, topographic map, etc.)

4.4 Atmospheric Correction

Remotely sensed spectral imagery of the Earth's surface can be used to the fullest advantage only when the influence of the atmosphere has been removed and the data are reduced to units of reflectance, especially when dealing with multi-temporal data and when a comparison of different sensors is required (Adler-Golden 1999).

The objective of an atmospheric/topographic correction (ATCOR) is the elimination of atmospheric and illumination effects to retrieve physical parameters of the Earth's surface such as surface reflectance, emissivity, and temperature (Richter 2005; Richter 1996; Adler-Golden et al. 2002; Asrar 1984; Baret and Guyot 1991; Carlson et al. 1995; Choudhury 1994; Huete 1998; Kaufman and Sendra 1988; Moran et al. 1994; Slater 1987). The ATCOR software was developed to cover about 80% of typical cases with a reasonable amount of coding (Richter 2005). An integral part of all ATCOR versions is a large database containing the results of radiative transfer calculations based on the MODTRAN4 code, the latest version of the well-known Moderate Resolution Atmospheric Transmission (MODTRAN) radiative transfer code developed by Spectral Sciences, Inc. (SSI) and the US Air Force Research Laboratory (AFRL), and now available through AFRL. The algorithm automates the MODTRAN4 radiance calculations used to construct the look-up tables (LUTs) needed for solving the retrieval (inverse) problem.[1]

Atmospheric correction has been carried out on each of the Landsat images (ETM+, TM, MSS) of the study area with ATCOR software to obtain surface reflectance. The main atmospheric parameters required for accurate atmospheric correction, such as aerosol type, visibility or optical depth, and water vapor, were defined according to the geographic condition of the study area and data obtained from the Keriya County meteorological station.

To investigate whether such a correction would be necessary for this study, the histograms of the Normalized Difference Vegetation Index (NDVI) values calculated from the digital number (raw data without calibration), exoatmospheric reflectance (calibrated data), and surface reflectance (data after atmospheric correction) were compared (Fig. 4.7).

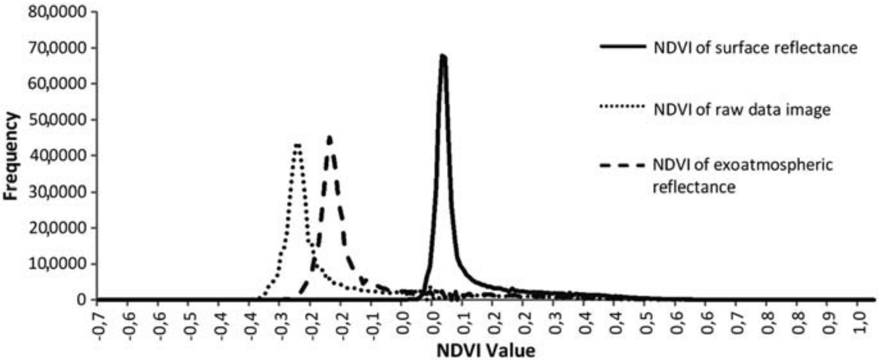

Fig. 4.7 Comparison of the NDVI histograms calculated from the raw data, exoatmospheric reflectance data, and surface reflectance data

Digital sensors record the intensity of electromagnetic radiation from each spot viewed on the Earth's surface as a digital number (DN) for each spectral band. The exact range of DN that a sensor utilizes depends on its radiometric resolution. For example, a sensor such as Landsat MSS measures radiation on a 0–63 DN scale, while Landsat TM measures it on a 0–255 scale. The majority of image processing has been based on raw DN values, where actual spectral radiances are not of interest. However, spectral signatures measured in digital numbers are not transferable, because they are image specific and depend on the viewing geometry of the satellite at the moment the image is taken, the location of the sun, specific weather conditions, and so on. Hence, it is far more useful to convert the DN values to spectral units, which can be compared from one image to another. The exoatmospheric reflectance relates the spectral radiance measured at the satellite sensor to the solar irradiance incident at the top of the atmosphere and is expressed as a decimal fraction between zero and one. While spectral radiances can be obtained from the sensor calibration, atmospheric interference still complicates the interpretation of remotely sensed information. Therefore, atmospheric correction must be done on the data to obtain a meaningful measure of radiance at the Earth's surface.

The NDVI histograms calculated from three different data types show that the NDVI values change considerably after atmospheric correction, as the atmospheric interference reduced the computed NDVI values. The mean and standard deviation values calculated from each of the three histograms also show such a change (Table 4.1). NDVI is a well-known vegetation index and is defined as the difference

Table 4.1 Mean and standard deviation values calculated from the histograms of three different data types

Data type	Mean	Stdv
Raw data (DN)	−0.100736	0.076532
Exoatmospheric reflectance	−0.093016	0.082614
Surface reflectance	0.099917	0.101658

between the red and near-infrared bands, divided by their sum. Atmospheric conditions can have different effects on near-infrared (NIR) and red light, and thereby influence NDVI values (Huete and Tucker 1991). The Landsat images used here were taken at different times of the year and with different sensors, atmospheric conditions, and sun angles. So, it is concluded that atmospheric correction is necessary in this study to get surface reflectance, providing more meaningful information and allowing comparison from one image to another, thereby making it possible to monitor environmental changes over time.

4.5 Soil Salinity Index (SSI)

Salinity is one of the most widespread soil degradation characteristics on Earth, and salinization problems are spreading at a rate of up to 2 million ha a year (Postel 1999). Salinization is the accumulation of soluble salts of sodium, magnesium, and calcium in soils (Mainguet 1991). High levels of soil salinity limit plant growth and crop productivity; the increased osmotic pressure of the soil solution reduces the plant's capacity to withdraw water from the soil (Ahmad and Kutcher 1992). Saline regions are found in poorly drained low-lying areas with semiarid and arid climates where large quantities of salts have leached from regions of higher elevation. These leached salts accumulate in the slow-flowing groundwater and are brought to the soil surface in these low-lying areas through high evapotranspiration rates (Goudie 1990).

Human activities can also cause salinization. In recent decades, the impact of humans on the circulation of salts in the landscape has been profound. Irrigation of cropland has led to the salinization of many soils. By adding more water—and inevitably more salt—to an area by irrigation, salts stored in deeper soil layers are mobilized. Another effect of irrigation is a rise in the water table locally, resulting in irrigated areas becoming waterlogged and salinized (Goudie 1990).

Remote sensing data have been widely utilized to detect, map, and monitor soil salinity. Remote sensing of surface features with aerial photography, videography, infrared thermometry, and multispectral scanners has been used intensively to identify and map salt-affected areas (Robbins and Wiegand 1990). Dwivedi and Rao (1992) noted that the digital analysis of multispectral data using the spectral response pattern of salt-affected soils is plagued by misclassification, and various image transforms must be developed to improve the detectability of these soils and other natural features using remote sensing data. These transforms not only enhance the detectability of these features but also aid data compression, resulting in substantially reduced computational time and cost. Spectral analysis and measurements made in the laboratory on salty soil by Mougenot (1993) show that the best absorption bands of the salt are located in the infrared domain of the spectrum. Wiegand et al. (1994) assessed the extent and severity of soil salinity in fields in terms of economic impact on crop production and effectiveness of reclamation efforts. Their study emphasized practical ways of combining image analysis capabilities, spectral observations, and ground truth to map and quantify the severity of soil salinity and its effects on crops. Band ratios of visible to near-infrared and between infrared bands have proven to be better for identifying salts in soils and salt-stressed crops than individual bands (Craig et al. 1998). Metternicht and Zinck (1997) combined digital image classification with field observation of soil degradation and laboratory analysis to map salt- and sodium-affected areas in the semiarid valleys of Cochabamba, Bolivia. Srivastava et al. (1997) studied the accuracy of mapping shallow groundwater depth and salinity using remote sensing data. In their study, groundwater depth and salinity maps were based on reflectance variations of vegetation above the ground surface, and they assert that the species of vegetation found in an area and vegetation densities can provide evidence of shallow groundwater conditions. Eldiery et al. (2005) used the stepwise regression method to find the best correlation between soil salinity data and corresponding pixel values on the satellite image bands, and found that the green band, the near-infrared band, and the near-infrared band divided by the red band ratio are strongly related to soil salinity.

By analyzing the spectral behaviors of the salty soils in the study area, and after testing numerous combinations of Landsat TM or ETM+ bands, a remote sensing model of soil salinity, called the Soil Salinity Index (SSI), is presented as follows:

$$SSI = \frac{PB^2 - PMIR_5^2}{PB^2 + PMIR_5^2}$$

$$PB = a_0 + a_1B_2 + a_2B_3 + a_3B_4 + a_4B_5 + a_5B_6 + a_6B_7$$
$$PMIR_5 = c_0 + c_1B_1 + c_2B_2 + c_3B_3 + c_4B_4 + c_5B_6 + c_6B_7$$

Where a_0, a_1, a_2, a_3, a_4, a_5, a_6, c_0, c_1, c_2, c_3, c_4, c_5, c_6 are coefficients of the model estimated with the method of least squares; B_1, B_2, B_3, B_4, B_5, B_6, B_7 represent respectively the Band 1, Band 2, Band 3, Band 4, Band 5, Band 6, and Band 7 reflectance values of Landsat ETM + or TM. So, PB is, in fact, the predicted value of the pixel's Band 1 (Blue) by least-squares fitting, using Band 2, Band 3, Band 4, Band 5, Band 6, and Band 7 as predictors. $PMIR_5$ is the predicted value of Band 5 (mid-infrared or MIR) by least-squares fitting, using Band 1, Band 2, Band 3, Band 4, Band 6, and Band 7 as predictors.

Figure 4.8 shows the SSI image calculated from the Landsat ETM+ image of the study area acquired on October 7, 2002. The index values have been divided into six classes ranging from nonsaline soil to very highly saline soil. The classes are named as SSI_class1, SSI_class2, SSI_class3, SSI_class4, SSI_class5, and SSI_class6. The class numbers correspond to the different degrees of salinity in ascending order: non-saline soil, very low saline soil, low saline soil, medium saline soil, high saline soil, and very high saline soil. The classes are defined primarily on the basis of field investigation data on soil salinity, a soil salinity map, and a general land use map of Keriya County. Surface water and desert, including gravel surfaces in the south of the study area, are separated and presented as two distinct classes. The desert occupies about two-thirds of the study area's surface, and features such as desert

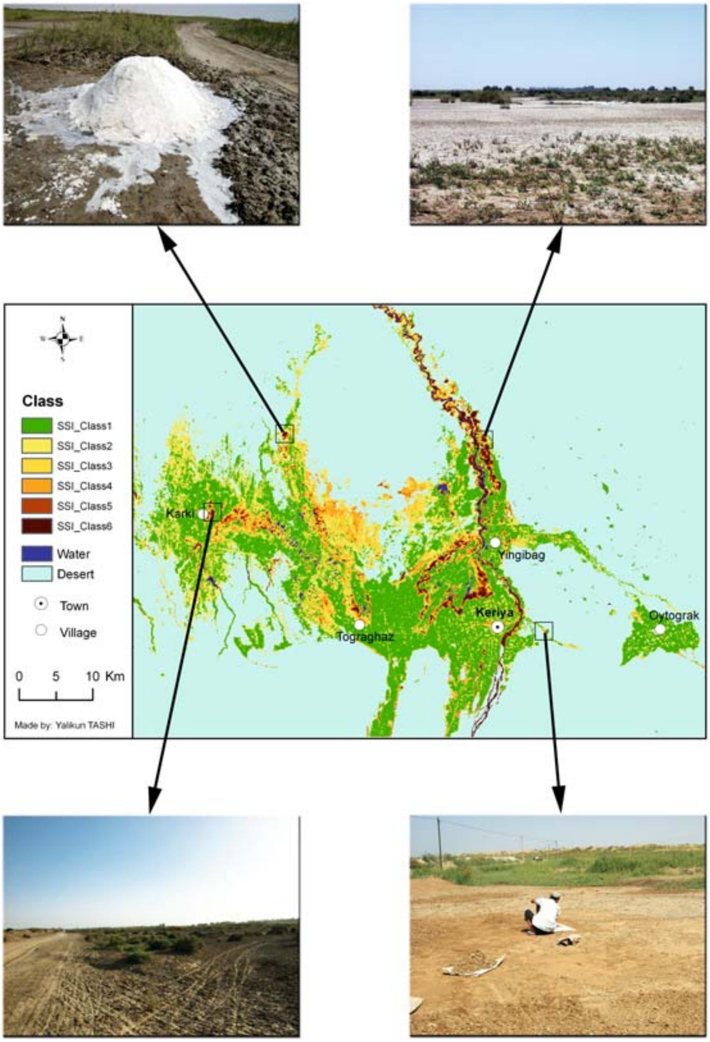

Fig. 4.8 SSI (Soil Salinity Index) image calculated from the Landsat ETM+ image acquired on October 7, 2002, and photos showing the surface state of salt-affected soils in different parts of the study area. The class numbers correspond to the different degrees of salinity in ascending order. (See also Plate 3 on p. 337 in the color plate section)

pavements, calcium carbonate and gypsiferous surfaces, and gravelly surfaces have spectral reflectance overlaps with saline soils. Hence, separating the desert has permitted not only concentrating the study rapidly on the area of interest (oasis and ecotone), but also avoiding confusion in the SSI values caused by some desert surface features. As to surface water, it has been found that the SSI is not capable of distinguishing surface water from highly saline soil, so it is very important to

Table 4.2 Confusion matrix calculated from the classification result and ground truth information (Pixel)

True class Assigned class	SSI_Class1	SSI_Class2	SSI_Class3	SSI_Class4	SSI_Class5	SSI_Class6	Total
SSI_Class1	5	0	0	0	0	0	5
SSI_Class2	0	4	0	0	0	0	4
SSI_Class3	0	1	3	1	0	1	6
SSI_Class4	0	0	1	3	0	1	5
SSI_Class5	0	0	1	0	3	0	4
SSI_Class6	0	0	0	1	2	6	9
Total	5	5	5	5	5	8	33

identify and separate the surface water before calculating the SSI values. The separation of surface water and desert can be done easily by applying unsupervised classification methods to the spectral bands of satellite images.

To show the accuracy of the SSI classes, an overall accuracy, kappa coefficient, confusion matrix, and errors of commission and omission have been calculated with the help of 33 ground truth sample points where soil salinity was investigated during field work in October 2002. The accuracy assessment has shown an overall accuracy of 72.73% and a kappa coefficient of 0.6689. The confusion matrix and the errors of commission and omission are shown respectively in Tables 4.2 and 4.3.

Table 4.3 shows that the classification accuracy is higher for highly saline soil than for medium or low saline soil. This is mainly because of the interference of salt-tolerant vegetation. Wilson and Tueller (1987) reported that soils in arid regions differ greatly in their spectral response and contribute significantly to the overall spectral response when the vegetation cover is below 25–35%. However, vegetation type, density, and spatial distribution can affect accurate detection of the underlying soil salinity. Numerous other elements, such as spectral behavior of salt types, temporal changes in salinity, and spectral signature confusion with terrain surfaces have also been reported as limiting factors for the use of remote sensing data for mapping salt-affected areas (Metternicht and Zinck 1997).

Table 4.3 Errors of commission and omission calculated from the classification result and ground truth information

Class	Soil salinity	Commission (Percent)	Omission (Percent)	Commission (Pixel)	Omission (Pixel)
SSI_Class1	Nonsaline soil	33.33	25.00	3/9	2/8
SSI_Class2	Very low saline soil	25.00	40.00	1/4	2/5
SSI_Class3	Low saline soil	40.00	40.00	2/5	2/5
SSI_Class4	Medium saline soil	50.00	40.00	3/6	2/5
SSI_Class5	High saline soil	0.00	20.00	0/4	1/5
SSI_Class6	Very high saline soil	0.00	0.00	0/5	0/5

4.6 Analysis of Oasis Environment Evolution by Multi-temporal Data

For 50 years, human activities such as land clearing, cropland extension, bad irrigation practices, and poor water management have led to a considerable acceleration of environmental degradation that has profoundly changed the oasis landscape in Keriya County.

To elucidate this evolution, it is useful to divide the study area into three regions: desert, oasis, and ecotone. In geography, an oasis is an isolated area of vegetation in a barren desert. Oases are found near a water source where groundwater is sufficiently close to the surface. In more common language, the word oasis is used to describe a small space in the desert that is made fertile by the presence of water. However, in its archaeological definition, an oasis is a land created by human hands and maintained by the introduction of an irrigation system. In fact, it is an area placed under cultivation by irrigation, so it is an artificial ecosystem. When dividing the study area into three regions, the word oasis takes the archaeological definition.

As a transitional belt between oasis and desert, the ecotone plays a very important role in the protection and stability of the oasis ecosystem. This role of the ecotone is mainly determined by the vigor and extent of its natural vegetation cover, as the destruction of vegetation cover due to human activities has been considered the main cause of environmental degradation or desertification in the Tarim Basin (Wang 1998). Information about the state of vegetation can be obtained from remote sensing data by calculating NDVI. Higher NDVI values are associated with greater density and greenness of the plant canopy, while barren soils are close to zero. Open water bodies such as rivers and lakes generally have negative NDVI values.

To extract information about land surface state changes and analyze their environmental impact, each of three satellite images of the study area acquired in three different years (1977, 1991, and 2002) first have been classified into three classes by their spectral signatures: desert, oasis, and ecotone. In each of the resulting three-class images, the ecotone class has been further subdivided into seven classes according to pixel NDVI values calculated from the original satellite images. The classes were named NDVI_class1, NDVI_class2, NDVI_class3, NDVI_class4, NDVI_class5, NDVI_class6, and NDVI_class7; the higher class numbers indicate higher NDVI values and thus greater density and greenness of vegetation. The results of the classification are shown in Figs. 4.9, 4.10, and 4.11, corresponding respectively to the images of 1977, 1991, and 2002. Such a classification not only allows identification of changes occurring over time in three major components (desert, oasis, and ecotone) of the landscape in terms of area, but also makes it possible to understand vegetation cover changes occurring within the ecotone due to human activities such as land clearing, extension of the irrigation network, overgrazing, and firewood collection. Two SSI images have also been calculated from the images of 2002 and 1991 and classified into six salinity classes (Figs. 4.12 and 4.13) as described in the previous section. Surface water and desert areas were separated as two distinct classes unrelated to the salinity classes. The two SSI images provide

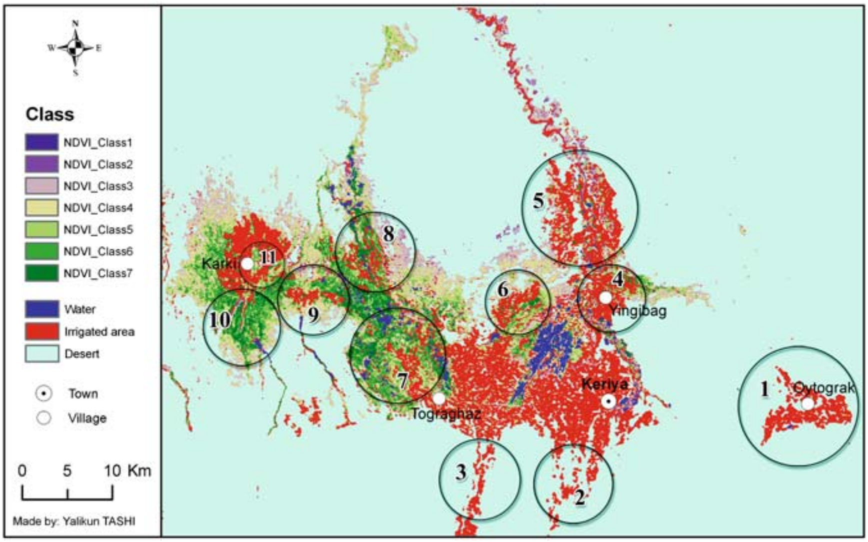

Fig. 4.9 Classification image of Landsat MSS acquired on June 23, 1977. The classes from NDVI_class1 to NDVI_class7 were obtained by binning[4] the NDVI values; higher class numbers indicate higher NDVI values and thus greater density and greenness of vegetation. (See also Plate 4 on p. 338 in the color plate section)

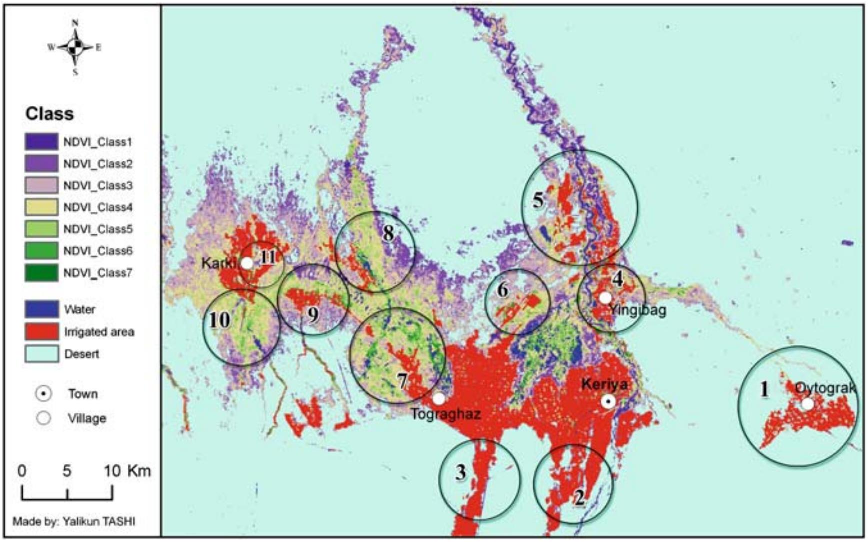

Fig. 4.10 Classification image of Landsat TM acquired on October 17, 1991. The classes from NDVI_class1 to NDVI_class7 were obtained by binning the NDVI values; higher class numbers indicate higher NDVI values and thus greater density and greenness of vegetation. (See also Plate 5 on p. 338 in the color plate section)

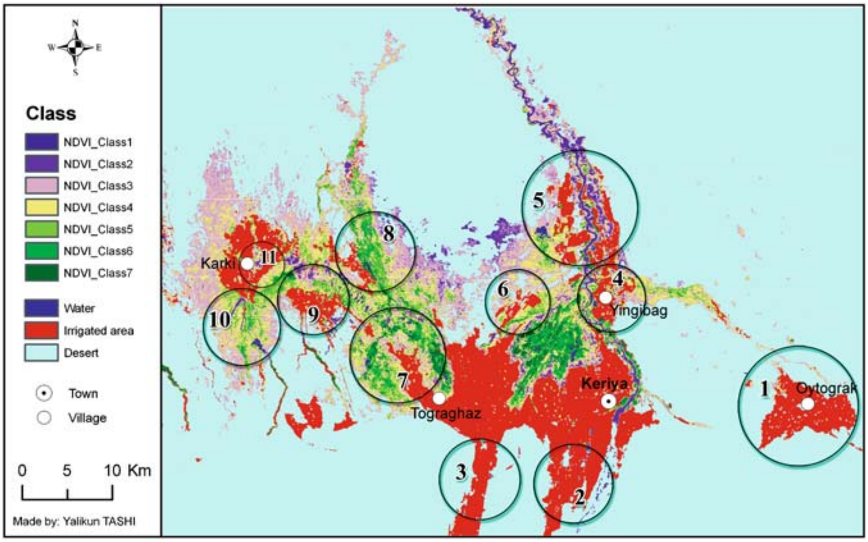

Fig. 4.11 Classification image of Landsat ETM+ acquired on October 7, 2002. The classes from NDVI_class1 to NDVI_class7 were obtained by binning the NDVI values; higher class numbers indicate higher NDVI values and thus greater density and greenness of vegetation. (See also Plate 6 on p. 339 in the color plate section)

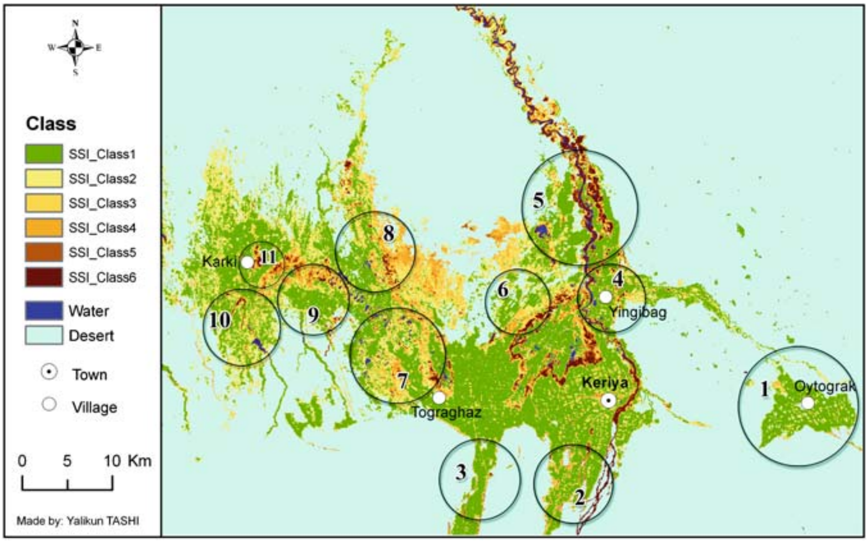

Fig. 4.12 SSI (Soil Salinity Index) calculated from Landsat ETM+ image acquired on October 7, 2002. Class numbers correspond to different degrees of salinity in ascending order. (See also Plate 7 on p. 339 in the color plate section)

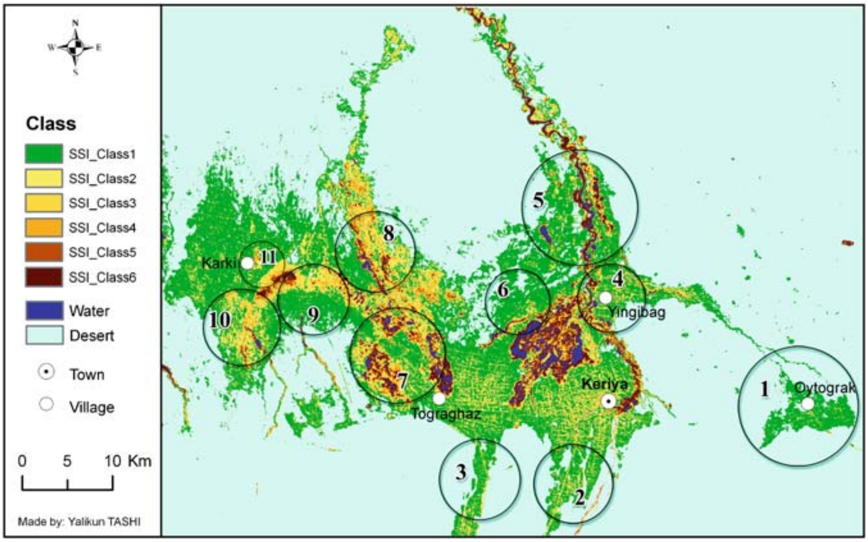

Fig. 4.13 SSI (Soil Salinity Index) calculated from the image acquired on October 17, 1991. Class numbers correspond to the different degrees of salinity in ascending order. (See also Plate 8 on p. 340 in the color plate section)

useful information about the extent of salt-affected soils and their spatial and temporal variation. Some locations are circled in Figs. 4.9, 4.10, 4.11, 4.12, and 4.13 to facilitate the comparative analysis of changes that occurred in different parts of the study area in terms of area, vegetation cover and condition, and soil salinity.[2]

Keriya County covers 39,100 km^2 and comprises 13 villages and three state-owned farms. According to literary and historical sources, the oasis of Keriya County (called Yutian in Chinese) was inhabited by 2,000 to 4,000 families—approximately 20,000 to 30,000 people—in the first century AD, at the height of the Silk Road trade. In the last quarter of the nineteenth century, the oasis of Keriya County and the adjacent oasis of Niya County (called Minfeng in Chinese) together were home to about 20,000 families (about 100,000 people). According to statistics from 1936, 1941, and 1948, Keriya had a population ranging from 80,000 to around 90,000 inhabitants. Between 1949 and 2004, the population increased more than 2.6 times, to 224,900 people (Fig. 4.14).

In itself, that tripling of the population implies a corresponding tripling of basic needs. But in reality, the needs of the population today differ from those in the 1950s. In the past 50 years, the ideology of modernization replaced that of production. In addition, the social revolution of the 1960s pushed to the fore the development of productive forces in the framework of the people's commune. Thus, from 1958, the Keriya County oasis area was gradually reorganized and new lands were cleared in the north, in particular in the state-owned farm No. 2.

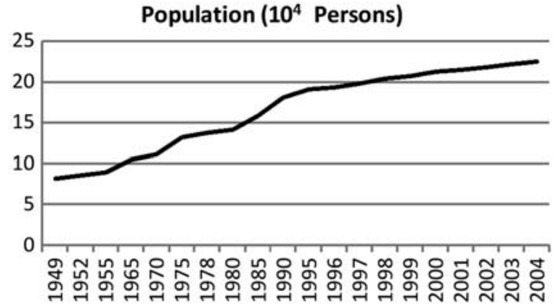

Fig. 4.14 Population growth of Keriya County (1949–2004)

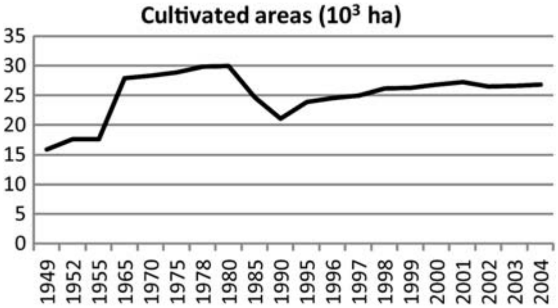

Fig. 4.15 Evolution of the cultivated areas in Keriya County (1949–2004)

Figure 4.15 shows the evolution of cultivated area from 1949 to 2004 in Keriya County. Irrigation has expanded since 1949 with the increase in cultivated land. Agricultural water consumption increased from 300 million m^3 in 1949 to more than 600 million m^3 in 1980. Thus Figs. 4.9, 4.10, and 4.11 show cultivated areas increased since 1977 in Oytograk (circle1), in the south of the Keriya oasis (circles 2 and 3), and in Laysu (circle 9), and the extension of cultivated lands and the irrigation system contributed to a transformation of some desert areas into oasis. However, it is precisely this extension of the croplands and irrigation networks that explains the increased soil salinization and abandonment of cultivated lands in some places.

In Figs. 4.9, 4.10, 4.11, 4.12, and 4.13, the class "water" shows potential waterlogged places in low areas, but its extent varies with the timing of image data acquisition, showing the temporal and seasonal variation of shallow groundwater depth in connection with agricultural water use. Thus, understandably, the soil salinity is very high around these areas, as shown in the two SSI class images (Figs. 4.12 and 4.13). In 1977, the irrigated area was larger than in 1991 and 2002 in Yingibag (circle 4, Figs. 4.9, 4.10, and 4.11), to the north of Yingibag (circle 5), and in state-owned farm No. 2 (circle 6). The significant rise of groundwater levels, and thus increased soil salinization, forced farmers to abandon their plots. The SSI images illustrate this transformation of soil surface state (circle 5, Figs. 4.12 and 4.13).

The ecotone was deeply affected by human activities from 1977 to 2002. Net changes in vegetation cover and an increase in salt-affected surface can be observed in the classified images. In 1977, the areas with high vegetation cover were larger than in 1991 and 2002, including south of the Karki oasis and the west and northwest of Tograghaz (circles 7, 8, 9, and 10, Figs. 4.9, 4.10, and 4.11). The salt-affected area increased between 1977 and 2002; high vegetation cover areas in 1977 indicated by circles 5, 8, 9, and 11 in Fig. 4.9 show increasing soil salinity in the SSI classification images of 2002 (Fig. 4.12). Land clearing, overgrazing, mismanagement of the irrigation network, and increasing soil salinity in waterlogged areas are the main causes of degradation of the ecotone. Overgrazing has occurred in the areas located at the periphery of irrigated sectors and villages; the number of domestic livestock increased from 180,000 in 1949 to 732,200 in 2004 (Fig. 4.16). Destruction of vegetation cover on sandy lands has led to widespread wind erosion, depletion of soil fertility, and the undertaking of expensive erosion control and vegetation cover protection efforts by local authorities. These efforts have been successful only in the oasis of Qira County (called Cele in Chinese, about 100 km west of Keriya County), thanks to the existence of an experimental station of the Chinese Academy of Sciences and to state control.

Reclamation of salt-affected soil can be achieved through water management. The most common methods of salt removal include the physical removal of salts by flushing or leaching (Gupta and Gupta 1987).[3] Leaching is the process of applying excess water to the soil surface to push the salts down through the soil profile along with the water. To permanently improve salinized soil, it is necessary not only to leach the soil, but also to have adequate drainage. The drainage system must provide an outlet for the removal of the leached water as well as keep the water table deep enough to prevent salt-laden groundwater from moving up to the root zone. This is particularly a problem for soils with a shallow, saline water table (Schilfgaarde 1974). Moreover, most of the canals of the irrigation network in the study area were not lined. Seepage from canals, distributaries, and field water courses is one of the main sources of excess groundwater which results in a raised water table. As much as 25% of the water can be lost into the ground through canal seepage, and therefore

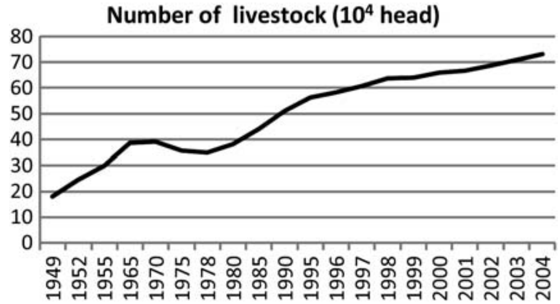

Fig. 4.16 Evolution of the number of domestic livestock in Keriya County (1949–2004)

lining the canal system is very important for more efficient use of irrigation water and prevention of secondary salinization induced by a rise in the water table.

The continued extension of irrigated areas in the upstream portion of the Keriya River has reduced the water supply available in the downstream portion, causing the destruction of most of the riparian poplar forest (Debaine-Francfort and Abduressul 2001) (see Chapter 12). Agricultural and pastoral activities of many villages along the downstream river banks also have been impeded by water shortage, leading to the departure of inhabitants. The Keriya River, which stretched in the 1950s to the dunes of the Taklimakan Desert, about 240 km north of Keriya Town, today barely reaches the village of Darya Boyi, 120 km away from Keriya Town. Today, people in Darya Boyi do not practice agriculture due to the lack of water, but with the help of dams, they distribute water through various arms of the delta to support the growth of poplars and the livestock (primarily sheep) that eat poplar leaves. So, to some extent, the western arms of the delta are irrigated artificially but with more and more difficulty due to a diminished flow. The lakes that existed between 1960 and 1986 in the delta have disappeared, the dried basins are occupied by dunes, and the poplar trees are threatened by the lack of water (Cheng 1991).

Finally, a rapidly growing population and limited land and water resources mean that combating environmental degradation is very difficult for this region. Land pressures must somehow be relieved, and that can only be accomplished by good agricultural policies and an increase in productivity and yields per unit area.

In Keriya County, the amount of land allocated to each household is very small and is usually divided into several parcels. The patchwork of plots makes the use of agricultural machinery impossible and requires continuous maintenance of the irrigation networks. Therefore, in order to improve production, consolidating land parcels is essential.

4.7 Methodological Perspectives

Human-induced soil salinization is a major environmental hazard in the oasis of Keriya County. Monitoring changes in soil salinity and identifying when, where, and how soil salinization may occur is vital to determining the sustainability of the oasis ecosystem maintained through irrigation. Remote sensing has been shown to be a particularly valuable tool for obtaining relevant data on soil salinity in the irrigated area. With an overall accuracy of 72.7%, the SSI presented here is capable of detecting soil salinity. However, confusion can occur between surface water and highly saline soil, so surface water area must be masked in the image to avoid such confusion. In addition, the accuracy of SSI is lower in low or medium saline soil, mainly because of the interference of salt-tolerant vegetation cover.

To increase the accuracy of soil salinity maps, it is important for future research to indirectly detect soil salinity through the biophysical characteristics of vegetation, as these are affected by salinity. The atmospheric correction accomplished by the ATCOR method makes it possible to carry out a multi-temporal analysis from the multi-sensor satellite images acquired in different years. Information derived from multi-temporal remotely sensed data such as SSI, NDVI, and different land use classes, and analysis of their spatial and temporal variations, can provide very meaningful information about changes in the oasis environment. Rapid population growth, extension of irrigated areas, poor management of irrigation water, inadequate agricultural policy, accelerated destruction of vegetation cover, and overgrazing are at the root of the increasing soil salinization and degradation of the ecological environment in this region.

Notes

1. The correction steps and equations involved in the ATCOR software, as well as the theoretical background of atmospheric correction, are not discussed here; they are available in the scientific literature (e.g. Richter 2005; Berk et al. 2003).
2. The recent evolution of the Keriya County oasis was analyzed by coupling all this satellite-derived information with historical, statistical, and socioeconomic data for the study area provided by local authorities such as the Bureau of Land Management and Planning of Keriya County and the Statistical Bureau of Keriya County.
3. During our field investigations, it was noticed that farmers were practicing the leaching method but without great success due to the lack of an appropriate drainage system.
4. Binning is a way of categorizing a continuous range of numerical data values into a manageable number of discrete classes or “bins.”

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Chapter 5
High Demand in a Land of Water Scarcity: Iran

Gholamreza Zehtabian, Hassan Khosravi, and Marzieh Ghodsi

Abstract Since ancient times, humans have mobilized huge efforts to counter water shortages and meet water demands in arid and semiarid areas. If, however, water issues existed on a local scale in the past, in the present and future these problems occur on national, regional, and global scales and could threaten peace keeping, food security, and eventually sustainable development. In Iran, a nation covering about 1,650,000 km^2, the supply, transfer, and use of water are major concerns, just as they were in ancient times. At present, about 55% of the water consumed in Iran is provided from groundwater resources and 45% from surface water, and more than 90% of water resources are allocated to the agriculture sector. The freshwater shortage has caused an increase in saltwater consumption, especially in arid and semiarid zones. Misuse and unrestrained water resources and traditional irrigation systems have caused soil salinity, land degradation, and desertification problems. Increasing salinity in most water resources in Iran over the past 10 years has caused an intensive decline of soil and water quality. Therefore, one of the main economical and social strategies of the government of Iran must be management that optimizes the use of water resources to attain sustainable development.

Keywords Groundwater · Iran · Irrigation · Qanat · Water resources

5.1 Water Crisis

Humans have grappled with nature to meet their water demands since ancient times, particularly in arid and semiarid regions. If, however, water issues and problems were posed on a local scale in the past, in the present and future these problems, which now constitute a water crisis, exist on national, regional, and global scales and could threaten peace keeping, food security, and eventually sustainable development.

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G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
DOI 10.1007/978-90-481-2776-4_5,

In Iran, a nation covering about 1,650,000 km^2, the supply, transfer, and use of water are major concerns, just as they were in ancient times. The population totals about 69.5 million (2006), of which 39% is rural. The remaining 61% lives in urban areas, up from 47% in 1986 (Iranian National Committee on Irrigation and Drainage 2002a, b). This rapid urbanization has increased the domestic and industrial demand for water.

Water consumption in Iran totaled 4.44 billion m^3 in 1963. This number increased to 83 billion m^3 in 1993 and 93.36 billion m^3 in 2006 (Amiraslani and Zehtabian 2006; Mohammadian and Zehtabian 2006). Per capita water consumption was 7,000 m^3 in 1956, but because of population growth, it decreased to 2,160 m^3 in 1996 and to 1,900 m^3 a decade later. It is predicted that per capita water consumption will drop to 1,300 m^3 in 2020 (Mohammadian and Zehtabian 2006). The renewable water resources available annually total about 2,150 m^3 per capita (Mohammadian and Zehtabian 2006).

Despite the water shortage, the major problems in Iran are the overuse of water resources, traditional irrigation systems, municipal and industrial wastewater, and contaminated drainage water from agriculture to groundwater (Khosravi 2005; Zehtabian and Amiraslani 2006). On the other hand, the water crisis has caused an increase in saltwater consumption in the agriculture sector, especially in arid and semiarid zones, as well as soil salinity, land degradation, and desertification problems (Khosravi 2005; Zehtabian and Amiraslani 2006).

5.2 Rainfall

Annual rainfall in Iran ranges from less than 5 mm in the deserts to more than 1,600 mm in the Caspian Sea basin (Amiraslani and Zehtabian 2006; Mohammadian and Zehtabian 2006). The average annual rainfall in the country is 252 mm, and about two-thirds of Iran receives less than 250 mm of rainfall per year. The distribution varies from region to region. The north, west, and southwestern regions cover only 30% of the total area of the country and receive more than 56% of the total rainfall. The central and eastern parts of Iran cover about 70% of the total land area, yet their share of rainfall is only 43%. The average annual rainfall in some parts of the Central Plateau is about 50 mm; annual evaporation may exceed 4,000 mm (Amiraslani and Zehtabian 2006).

The main source of water is rainfall, estimated at approximately 415 billion m^3/yr. From this amount, 93 billion m^3 is surface flow and 25 billion m^3 penetrates into alluvial aquifers. The surface runoff to the sea and to other countries is estimated at 55.9 billion m^3, and the remaining amount evaporates from land surfaces, pastures, and forests. About 12 billion m^3 enters Iran through rivers that combine with surface flows and stored water in alluvial aquifers to total 123 billion m^3. Iran's renewable water resources amount to 135 billion m^3 (Amiraslani and Zehtabian 2006).

The six major basins in Iran are the Caspian Sea, Persian Gulf, Uremia Lake, Central Plateau, Eastern Border, and Ghare-Ghoom (Table 5.1). But for state water

Table 5.1 Rainfall in major basins of Iran

Basin	Total area (km^2)	Rainfall (billion m^3)	Major river
Caspian Sea	174,385	79	Aras
Persian Gulf and Sea of Oman	423,305	153	Karoon, Dez
Uremia Lake	51,865	25	Aji-Chay, Zarineh-Rood
Central Plateau	842,000	128	Karaj, Saveh
Eastern Border	111,845	22	Harirood, Hirmand,
Ghara–Ghoom	44,600	13.5	Kashfrood
Total	1,648,000	420.5	

Source: Amiraslani and Zehtabian 2006

resources management, the country is divided into eight basins and 37 sub-basins, in accordance with results of a comprehensive survey (Tamaab Organization 2004). The eight basins are North and Sefid Rood; Azerbaijan; Khuzestan and the West; Fars and Hormozgan; Kerman, Systan, and Bloochestan; Isfahan and Yazd; Tehran and Markazi; and Khorasan (Fig. 5.1).

5.3 Agriculture Water Consumption

Approximately 93.36 billion m^3 of surface water and groundwater is used annually in Iran (Zehtabian 2003). Of that, more than 93% is used for agriculture and fish breeding, while less than 7% is allocated for domestic, mining, and industrial uses. The existence and importance of groundwater has been known and understood for thousands of years. However, due to emerging water demands and a shortage of surface water, farmers are attempting to use more and more groundwater for their crops. The use of groundwater for irrigation purposes is much higher in Iran than in many other countries, including China, Pakistan, Mexico, Argentina, and Morocco (Table 5.2).

The agriculture sector in Iran is one of the most important economic sectors of the country, and water scarcity is the most limiting factor for agriculture expansion and higher production. In an attempt to increase self-sufficiency in food production, Iran allocates more than 90% of its water resources to agriculture (Table 5.3).

The necessary increase in agriculture production can be obtained only through technical and scientific methods that boost agriculture water productivity (Gharaman and Sepaskha 1997). This productivity is defined as the amount of crop production per unit amount of water applied for irrigated crops (Barker and Dawe 2001), or per millimeter of precipitation for dry land farming crops, which is presently about 0.8 kg/m^3. This is very low; production must increase to about 1.6–2 kg/m^3 by 2020 to meet the projected demand for food and other agriculture products (Zehtabian 2003).

Fig. 5.1 Main basins and sub-basins of Iran. (Source: Tamaab 2004)

Table 5.2 Groundwater use for irrigation in selected countries

Country	Irrigated area (million ha)	Irrigation use (km^3/year)	Proportion of groundwater (%)
India	50.1	460	53
China	48.0	408	18
Pakistan	14.3	151	34
Iran	7.3	64	50
Mexico	5.4	61	27
Bangladesh	3.8	13	69
Argentina	1.6	19	25
Morocco	1.1	10	31

Source: Qureshi 2004

Table 5.3 Average amount of water applied to different crops for irrigation in Iran

Crop	World average (m^3/ha)	Iran (m^3/ha)
Wheat	4,500–6,500	6,400
Melons	7,000–10,500	17,900
Sugar-beet	5,500–7,500	10,000–18,000
Rice	4,500–7,000	10,000–18,000
Sugarcane	15,000–25,000	20,000–30,000
Corn	5,000–8,000	10,000–13,000

Source: Keshavarz et al. 2003

Total irrigation areas cover approximately 5,350,000 hectares (ha), which is equivalent to 32.8% of Iran's cultivated areas. During the past 25 years, irrigation areas have doubled (Zehtabian 2003), and irrigation is very inefficient; 75% of the water volume that can be consumed in the agriculture sector is wasted. Global studies show that the countries that have changed their irrigation management and promoted modern methods, such as sprinkler and drip irrigation systems, increased their irrigation areas (Qureshi 2004). In Iran, more than 90% of the irrigation methods used are traditional. For example, basin and furrow systems make up more than 65% of the irrigation methods but have an efficiency rate of about 20%. Due to irrigation mismanagement, approximately 400,000 ha of agricultural lands are degraded every year, or around 1 million ha are added to the country's desert areas (Zehtabian and Amiraslani 2006).

5.4 Groundwater Resources

At present, about 55% of the water consumed in Iran comes from groundwater and 45% comes from surface water. Groundwater has always played an important role in developing agriculture in different parts of the country. Statistics show that the volume of water use from groundwater between 1988 and 2006 increased compared to surface water (controlled or uncontrolled) (Khosravi 2005).

The current estimated annual groundwater abstraction is about 55 billion m^3/yr, while the annual recharge is only 45 billion m^3. The groundwater table is declining in many areas because of this annual deficit of 10 billion m^3. Pumped groundwater is used for irrigation both in isolation and in conjunction with surface water, creating a serious salinity threat in irrigation areas.

The use of groundwater has played a key role in enhancing agriculture productivity and drought mitigation. In recent years, digging deep and semi-deep wells has taken a quantum leap in Iran. Current estimates put the number of wells today at about 470,000 compared to only 230,000 in 1990 (Mohammadian and Zehtabian 2006; Tamaab Organization 2004). Most of the wells are owned by private farmers with no limits on groundwater abstraction. This unsystematic and unregulated use

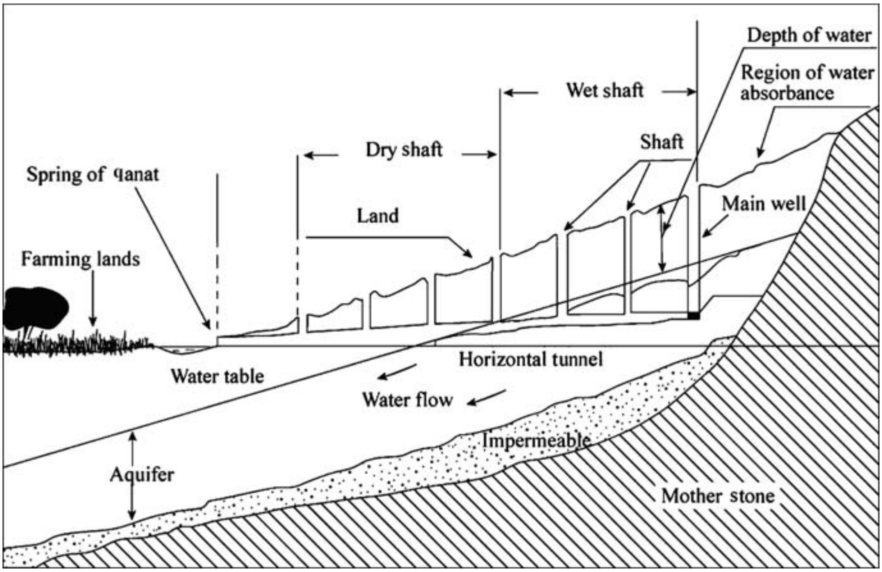

Fig. 5.2 Vertical cross section of a qanat. (Source: Mohammadian and Zehtabian 2006)

of groundwater for agriculture is replete with serious consequences, including the decline of the groundwater table.

Qanats—tunnel systems used to bring groundwater to the surface (Wulff 1968; Pearse 1973)—are still used in Iran, where they were developed about 2,500 years ago to meet inhabitants' water needs (Fig. 5.2) (see Chapter 8). Qanats exist in every province in Iran but are more numerous in the arid and semiarid zones. About 77% of these qanats are located in the central and eastern parts of the country. The most famous of these are found in Khorasan, Kerman, Yazd, Isfahan, and eastern Azerbaijan provinces (see Fig. 5.3). About 15% of the annual groundwater abstraction in Iran is obtained through the qanat system, which does not require electric energy or fossil fuels and minimizes environmental damage (Table 5.4).

Unfortunately, the emergence of new technologies has led to the destruction of qanats. In addition to causing a negative water balance in most areas, the excessive exploitation of water through deep and semi-deep wells has accelerated the trend towards desertification. However, many water and soil-related projects have been implemented in recent decades to recharge aquifers, including a typical plan for a ditch and flooding recharge system.

5.5 Soil and Water Salinization

Approximately 34% of soils in Asia are influenced by salts. With about 25 million ha of saline and alkaline lands—about 15% of the country—Iran has the most saline lands in Asia after China, India, and Pakistan due to its geographical position

Fig. 5.3 Political border map of provinces in Iran

and climate (Zehtabian and Amiraslani 2006). The expansion of saline and alkaline lands has increased with the spread of agriculture into areas without drainage systems. Increased salinity in most water resources in Iran has caused an intensive decrease of soil and water quality that in most areas has led to a drop or changes in cultivation.

Out of Iran's 93 billion m^3 of surface water, including flows, springs, and water from rivers, about 10.75 billion m^3, or approximately 11% of the total flowing water in the country, comes from rivers that have a salinity of more than 1,500 mg/L (Zehtabian and Amiraslani 2006) (Table 5.5). Most of these rivers are located in south, southwestern, and central Iran, and they are the only water resource for agriculture development in those areas (Kashkuli and Hosseinizare 2004).

Studies were conducted to assess and evaluate the status of soil and water resources of desertification sites. The results highlighted several factors that contribute to the salinization of water resources: the passage of water over salty geological formations; the application of conventional irrigation methods; mismanagement of water resources; over-exploitation of groundwater; mixing of fresh and salty water resources; inappropriate utilization of chemical fertilizers and pesticides; the occurrence of water and wind erosion; and the declining groundwater table coupled with increasing water salinity in many parts of the country[1] (Zehtabian 2003; Zehtabian and Sarabian 2004; Zehtabian and Amiraslani 2006).

Table 5.4 Total groundwater exploited by qanats in Iran*

Province	Qanat Number	Exploitation Volume (billion m^3)
Eastern Azerbaijan	1,973	0.33628
Western Azerbaijan	440	0.03008
Ardabil	107	0.02259
Isfahan	2,773	0.69282
Ilam	2	0.00009
Bohsher	46	0.010.42
Tehran	714	0.37795
Chahar Mahal Bakhtiari	459	0.06314
Khorasan	8,992	2.01349
Khuzestan	3	0.01249
Zanjan	692	0.10959
Semnan	641	0.1324
Sis tan and Baluchistan	1,321	0.53644
Fars	1,274	0.76168
Ghazvin	380	0.12026
Gom	1,191	0.39996
Kurdistan	250	0.0351
Kerman	1,636	1.23127
Kerman shah	250	0.05336
Kikuyu and buyer Ahmad	33	0.01852
Golestan	297	0.07153
Gailan	102	0.03409
Lorestan	1,527	0.34024
Mazandaran	63	0.035.03
Markazi	2,339	1.16397
Hormozgan	78	0.03869
Hamadan	1,388	0.364
Yazd	2,972	0.33404
Total	31,943	9.29407

Source: Mohammadian and Zehtabian 2006

*The number of qanats and the exploitation volume may vary by author depending on sources used.

In Golestan province, natural and anthropogenic factors caused soil and water salinization. Natural salinization factors in this region were Caspian Sea sediments, geologic formations, topography, high evaporation, and low rainfall totals. Anthropogenic salinization indicators were irrigation systems, improper drainage systems, and industrial and domestic sewage.

In a 28-year period in Golestan province, about 2.4% of soils shifted from a low saline class (EC: 4–8ds/m) to a medium class (EC: 8–15ds/m), and 23.5% of the soils moved from a low to high saline class (EC>15ds/m) (Zehtabian et al. 2004).[2] In Semnan province, soil and water resources are being destroyed by the expansion of groundwater salinity, and the process of land salinization is the most important cause of desertification (Zehtabian et al. 2004). Water salinization factors in this region are geological formations and climate conditions; soil salinization is caused by improper irrigation (i.e., with saline water) and cultivating methods.

Table 5.5 Average volume of saline water with salinity of more than 3,500 µmhos/cm*

Name of River	Volume of saline water (billion m^3)
Gorgan Rood	0.452
Ghor Chay	0.022
Aji chay	0.450
Baba Haji	0.042
Heleh	0.934
Moond	1.180
Zayande Rood	0.178
Shoor	0.019
Kal	0.474
Jaj Rood	0.131
Ghore Chay	0.222
Harir Rood	0.504
Jam Rood	0.014
Moshkan	0.014
Kal Khoomik	0.002
Kal Shoor	0.011
Sangerd	0.005
Total	4.654

Source: Zehtabian and Amiraslani 2006
* micromhos per centimeter

5.6 Water Pollution

Iran has created extensive water pollution problems that are caused not only by physical and biological changes but also by an increasing amount of poisonous materials that make water unusable. Some of these pollutants, such as agricultural, human, and animal waste, degenerate into useful materials. However, some materials in sewage, such as mercury, lead, and some plastic composites, do not decompose. The pollution problems in Iran, like in other developing countries, occur at a greater rate than in industrial countries.

Karstic water—one of the most important drinking water supplies in Iran—is prone to contamination. The most important sources of pollution that can affect the quality of Iran's karstic water resources include urban sources, such as leakage from sewers and solid and liquid material in trash; industrial sources, such as leakage from tanks, mining activities, and oil spills; agricultural sources, including backwater from farming, animal manure, pesticides, chemical fertilizers, and insecticides; and microorganisms, hydrocarbons, pesticides, heavy metals, nitrogen compounds, radio-isotopes, and nonorganic compounds in water.

5.7 Iranian Water Resource Management

Nowadays, saline water resources and the possibility of recycling urban and industrial water, in conjunction with the development of technologies related to the use of marginal water resources, are generating hopes that mankind will be able to find suitable and economical approaches to meet water resources demands and reach sustainable development goals (Allan 1999).

The volume of saline water resources in Iran totals nearly 10–11 billion m^3 in surface water resources and about 1.7 billion m^3 in groundwater—nearly two times the volume that could be taken from the biggest dam in the country (Karkheh) (Iranian National Committee on Irrigation and Drainage 2003). In addition, the volume of agriculture wastewater is nearly 29 billion m^3, which is almost 30% of the water annually used in Iran. Using this volume of water is very effective in reducing water shortages. Furthermore, the volume of urban wastewater is significant; early estimates show that about 2.4 billion m^3 of wastewater near urban areas exists for proper usage in irrigation, recreation, and environmental conservation and could also reduce urban water demand for freshwater resources (Dinar et al. 2003).

Despite the shortage of water, the overuse of water in irrigation is a major problem. At present, a wide gap exists between water delivery from main canals and water application in the fields. The emphasis has been much more on water resources development than on water resources management. The overall efficiency rate of irrigation systems is around 25%. Currently, only 2% of the cultivated area is equipped with pressurized irrigation systems, and the remaining 98% is irrigated through traditional flood basin methods. Therefore, water resources management requires improving water use efficiencies, modernizing irrigation infrastructure, prioritizing water use, and enhancing management capacity. This will lead progressively to a transformation in the institutional structures and procedures of water allocation and use in the agriculture sector. Recently, steps have been taken to price surface water and groundwater use and to introduce high-efficiency irrigation systems.

5.8 Sustainability for Future Generations

It is more or less possible to meet the water demands of all of Iran and reach the point of self-sufficiency with the aid of financial and human—especially managerial—resources, the removal of organizational hurdles, and the mobilization of a national will. Water resources constitute an important factor limiting the development of agriculture. However, by controlling surface water resources, properly using groundwater resources, and constructing necessary facilities, up to 100 billion m^3 of water can be allocated to the agriculture sector. Access to this water has been projected for the year 2020, when Iran's population will total about 100 million people, and will allow 6–8 million ha of land to be put under irrigated cultivation (Iranian National Committee on Irrigation and Drainage 2002). Various regions of Iran are fit for 6 million ha of dry farming annually which, on the whole, can amount to a total of about 117 million tons of agriculture products.

To solve the water resources problems in Iran, water managers must make logical and effective decisions. Achieving this requires improving strategies and policies concerning water resources development and irrigation; coordinating water resources and irrigation development programs with agricultural policies and programs; constructing relatively inexpensive reservoirs and dams (Cabangon 1999); protecting natural resources and using them properly (Kadekodi 2001); and focusing on the fulfillment of training and promotion in agricultural programs. Adopting sound, long-term strategies to meet Iran's water demand is essential if sustainable development is to be achieved for future generations.

Notes

1. This last factor poses a major challenge for appropriate soil management and sustainable agriculture development. In the Kashan area, located in Esfahan province, for example, the water table declined by an average of 16 m between 1975 and 2003, representing an average withdrawal of 0.6 m/yr (Khosravi 2005).
2. EC refers to electrical conductivity and ds/m is the abbreviation for deciSiemens per meter.

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Chapter 6
Common Scarcity, Diverse Responses in the Maghreb Region

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Abstract The Maghreb region faces a large increase in population and water demand for both people and agriculture. At the same time, pollution of the aquifers has reduced hydrological reserves. With a net decrease in rainfall during recent decades and the expansion of rural activities (agriculture and livestock), demand for water in the Maghreb is less and less satisfied. To face this hydric stress, several strategies are required to increase the efficiency of existing resources and develop new ones. Appropriate technical responses call for new equipment to transfer and distribute water and require the mobilization of nonconventional water: implementation of new techniques of seawater desalination, new equipment to treat and recycle wastewater, and the reuse of the foggara system, also known as the khettara. From an "equity of access to water" viewpoint, national solidarity requires the transfer of water from areas of abundance towards areas less well endowed. In order to respond to people's needs while taking into account the unequal geographic distribution of water, it will become increasingly necessary to seek water from further away to sustain the cities. Coherent interventions require the design of new integrated strategies for the management of available water resources at all levels, including farmers, herders, municipalities, the private sector, and resource managers.

Keywords Arid Mediterranean climate · Arid zone · Maghreb · Water management · Water resources

6.1 Hydric Stress in the Maghreb

The Maghreb, a region in North Africa, is located between the Mediterranean Sea and the Sahara. It experiences major climate stresses, with inadequate and irregular rainfall, marked inter-annual and seasonal variability, intense evaporation, and high temperatures with strong diurnal and seasonal variation. With a present average of 1,000 m^3 of water per inhabitant per year, and less than 500 m^3 projected for the

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G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
DOI 10.1007/978-90-481-2776-4_6,

years to come, people in the Maghreb live with hydric stress that restricts their economic and social lives (see Chapter 13). While the population increased threefold during the twentieth century, the demand for drinking water multiplied by seven and the demand for irrigated agriculture by six. Moreover, pollution of the aquifers used has reduced hydrological reserves during the last 50 years. To face this hydric stress, several strategies are needed to increase efficiency in the use of resources and develop new ones. Such strategies have environmental, social, and economic costs, and they require the participation of new actors and partners from both public and private sectors.

6.2 Water Resources

Extending over 576,500 km^2, the arid and semiarid areas of the Maghreb have a Mediterranean climate, characterized by a long, dry summer season that varies from four to 12 months, depending on the degree of aridity: semiarid, arid, and hyperarid. The rainy season may occur in autumn, winter, or spring according to geographical position (Le Houerou 1984; Djellouli 1990). Most of the area is affected by this aridity, from the Mediterranean Sea (western coast of Algeria, southern Tunisia, and Morocco, and north Libya) through the highlands of Morocco, Tunisia, and Algeria (mainly pastoral areas). The area becomes more arid along the northern edge of the Sahara Desert. More than 120 million hectares (ha) of arid land is threatened by the processes of desertification, according to the United Nations Convention to Combat Desertification (UNCCD), with 445 million ha already considered desertified. Natural water resources are limited, and the spatial distribution and management of these different resources varies considerably depending on locality.

Despite its great diversity from a phytogeographical and orotopographical point of view, the Maghreb is generally subject to the Mediterranean climate with great interannual variability in precipitation (Fig. 6.1) and various bioclimatic stages. It is characterized by several degrees of aridity:

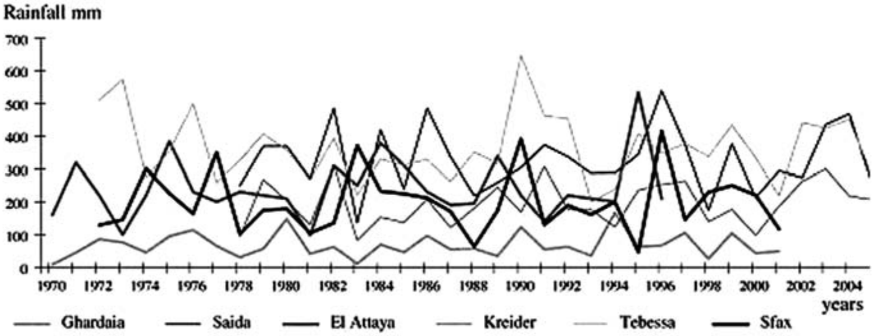

Fig. 6.1 Rainfall records for some stations, 1970–2005: Ghardaia, Saida, Kreider, and Tebessa (Algeria); El Attaya and Sfax (Tunisia)

- the semiarid zone receives annual rainfall that varies from 300 to 500 mm, corresponding to thickets of *Quercus ilex* (Holm oak), *Pinus halepensis* (Alep pine), *Tetraclinis articulata* (thuya), and *Juniperus phoenicea* (juniper of Phenicia) and to where the boundary for growing corn approximates with the 400 mm isohyet;
- rainfall in the arid zone totals between 150 and 300 mm per year with *Stipa tenacissima* (esparto), *Artemisia herba alba* (white armoise), and *Lygeum spartum* (Sparte) growing on the steppes of this zone;
- precipitation in the hyperarid zone rarely exceeds 150 mm and the zone contains clear steppes of *Hamada scoparium* (Remth) and other species adapted to an extreme aridity.

The dryness which currently prevails in the Maghreb began during the 1970s and has intensified ever since with exceptional persistence (Djellouli 1990; Meddi 2006; Hénia 1993). The recorded rainfall amounts show that the average rainfall has decreased in recent years. In the last decade, this deficit in Algeria was more than 20% for the western area, 13% for the central part of the country, and 12% for the east (Ould Amara 2000; Bouguerra 2001). The figures are similar for central and southern Tunisia and for Morocco (Moksit 2000). Depending on the season (Meddi 2006), the reduction of precipitation has decreased by as much as 20–40% at a certain number of stations in the Maghreb zone.

From a thermal point of view, several authors agree that while the maximum average temperatures have remained relatively stable during the twentieth century, the minimum temperatures show a slight increase. January remains the coldest month, while in July—the hottest month when the insolation is longest—the sirocco reaches its maximum, and evapotranspiration is high. Ould Amara et al. (2002) published monthly charts of potential evaporation by standard vegetative cycle, thus allowing locations without data to evaluate their real water needs.

Water scarcity in the Maghreb may appear paradoxical given the exceptional weather events that led to recent floods in several areas, including western and central Algeria, Sébou in Morocco, and Sfax in Tunisia.[1]

6.2.1 Surface Water

Renewable water resources include surface water and groundwater. Eighty percent of surface water resources are located in the north of the country, while 65% of groundwater resources are in the southern regions (Daoud 2004). The climatic conditions that occur over the largest part of the regions lead to temporally and spatially irregular renewable resources. Surface water depends on geographical hydrological factors within each country (Tables 6.1, 6.2).[2] Morocco is best equipped with abundant resources (16,500 cubic hectometers, or hm^3)—even if they are "impetuous," according to Pérennès (1993)—whereas Algeria's 9,500 hm^3 (Bouguerra 2001) is unequally distributed between the western north, which is less humid, and the center. As for Tunisia's 4,355 hm^3, 80% of the potential surface waters are located in the north of the country. The need for water is important inland (Daoud, 2004), and 65% of the groundwater is in the south of the country.

Table 6.1 Estimate of potential (available water), subject to mobilization (water extracted with existing techniques), and subject to regularization (real amount of extracted water) (hm^3)

	Potential			Subject to mobilization			Subject to regularization		
	Surface	Ground	Total	Surface	Ground	Total	Surface	Ground	Total
Morocco	25,000	7,500	30,000	16,000	5,000	21,000	12,000	4,500	16,500
Algeria	14,410	6,710	19,120	6,000	3,500*	9,500	5,000	3,500*	8,500**
Tunisia	2,630	1,725	4,355	2,102	1,725	3,827	1,697	1,725	3,422**

* about 5,000 hm^3 according to other sources (of which half are in the albian aquifer)
** other sources (ANRH, Algiers; SONEDE, Tunisia)
Source: International Water Management Institute (IWMI) 2000

Table 6.2 Useful and renewable water resources in the Maghreb countries (km^3/yr)

Countries	Natural renewable water resources (km^3/yr)	PUF*	Useful resources (km^3/yr)
Algeria	14	60	9
Morocco	30	65	20
Tunisia	4	60	2

Source: International Water Management Institute (IWMI) 2000
*Potential Utilization Factor

Table 6.3 Surface water resources. Surface water potentialities and reduction rates during the observation period in the twentieth century

Basins: west(w) center(c) east(e)	Areas (Km^2)	Contribution of dry periods (hm^3/yr)	Global contribution (hm^3/yr)	Reduction rates (%)
Cheliff (w)	43,550	1,078.3	1,540	30
Côtiers algérois (c)	11,972	1,536	2,850	46
Côtiersconstantinois (e)	11,566	2,753	3,250	15
Côtiers oranais (w)	5,831	33	50	34
Isser (c)	4,149	312	520	40
Kébir Rhumel (e)	8,815	700.6	910	23
Macta (w)	14,389	966		
Médjerda (e)	7,789	220	240	8
Seybouse (e)	6,475	359	450	20
Soummam ©	9,125	630	700	10
Tafna (w)	7,245	232	335	30
Chott Hodna (e)	25,843	156	220	29
Chott Melrhir (e)	68,750	240	300	20
H.P. constantinois (e)	9,578	105.2	135	22
H.P. oranais (w)	49,370	140		
Zahrez (c)	9,102	77	110	30
Sahara	100,000	200	320	37

Source: Bouguerra 2001

Table 6.4 Surface water resources. General repartition of surface water resources in Tunisia (1995) in Mm^3

Regions	North West	North East	Total North	Western center	Easter center	Total center	South West	South East	Total South	Grand Total
Resources	1,585	605	2,190	190	180	370	20	120	140	2,700

Source: Daoud 2004

These water resources are considered insufficient in the Maghreb, where the annual volume is often less than 1,000 m^3 per capita and is currently decreasing. According to Bouguerra (2001), the potential of the surface water resources in the north of Algeria, estimated at 13,500 hm^3 per year in 1979, was reevaluated at 12,410 hm^3 per year in 1986 and is more currently at only 9,700 hm^3 per year (Table 6.3). The resource is clearly declining, taking into account the dry conditions that have prevailed for the last three decades on all the basin slopes of northern Algeria (as testified by the actual state of dams). Daoud (2004) arrives at similar reports for Tunisia (Table 6.4).

6.2.2 Renewable Groundwater

Renewable groundwater is present at different depths. It is fed by the winter rains and the percolation from wadis[3]. The most exploited water tables are less than 50 m deep, where they are easier and less expensive to reach. A growing number of wells tap groundwater between 100 m and more than 600 m deep[4]. Various traditional and modern means are used to access these wells, including pulley and power-driven pumps.

6.2.3 Nonrenewable Aquifers

These resources are concentrated mainly in large basins and aquiferous systems and constitute a considerable potential. They are of strategic importance for the social and economic development of the Maghrebian arid areas and are represented by the water tables of the Continental Intercalary (fossil albian[5] aquifer). Discovered in 1954 in the Algerian Sahara, these water tables lie 1,300–2,000 m underground. The aquiferous system of the north Sahara, extending 1 million km^2, is shared by Algeria, Tunisia, and Libya.

The groundwater tables are fed by the winter rains and sometimes by infiltration from the wadis. The Maghrebian states encompass the largest part of the Sahara where important nonrenewable water tables exist (Fig. 6.2). In the south Algerian Sahara (Latrèche 2003) and in western Libya, water tables extend between 800 and 1,500 m underground; the huge albian aquifer has 60,000 billion m^3 of water. With equivalent storage, the Nubian aquifer extends into Egypt and eastern Libya. These

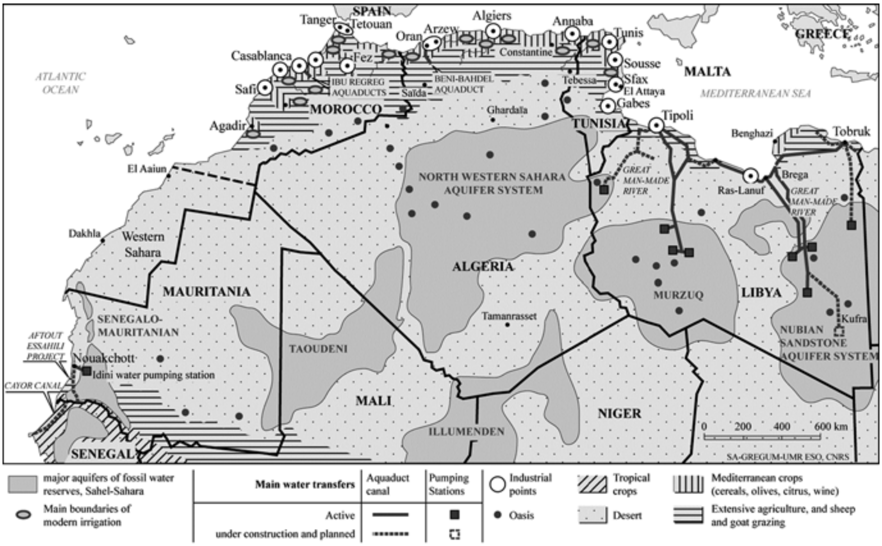

Fig. 6.2 Groundwater resources and main water transfers in North Africa. (Source: Rekacewicz 2006)

aquifers were formed during the rainy period of the Quaternary, and the magnitude of the water content encouraged exploitation. Irrigated agriculture in the full desert was attempted, but the expected results anticipated during the last few decades have not materialized.

Algeria, Tunisia, and Libya have launched efforts to coordinate the management of these water resources. The Aquiferous System of the Septentrional Sahara (SASS) is a program initiated by the international organization Observatory of the Sahara and the Sahel (OSS) to develop dialogue between the three countries. Its mission is to build a “basin conscience” by evaluating the water resources and the scenarios of long-term development, facilitating the exchange of information, and developing decision-making tools.

The number of pumping stations has multiplied between 1970 and 2000 (Fig. 6.3) (OSS 2001; Latrèche 2005). To date, more than 7,000 water points exist in the countries. In 2002, a SASS report noted that “the simple continuation of the current intensity of pumping can constitute a serious danger.” The volume of water pumped annually has increased by 525% in 50 years, from 0.4 billion m^3 in 1950 to 0.6 billion m^3 in 1970 and to 2.5 billion m^3 in 2000. The fact that these resources are nonrenewable makes them even more vulnerable and exhaustible in the long term (Latrèche in OSS 2005). Modeling of the aquifers allows a prospective and concerted management of water resources of the whole of the basin.

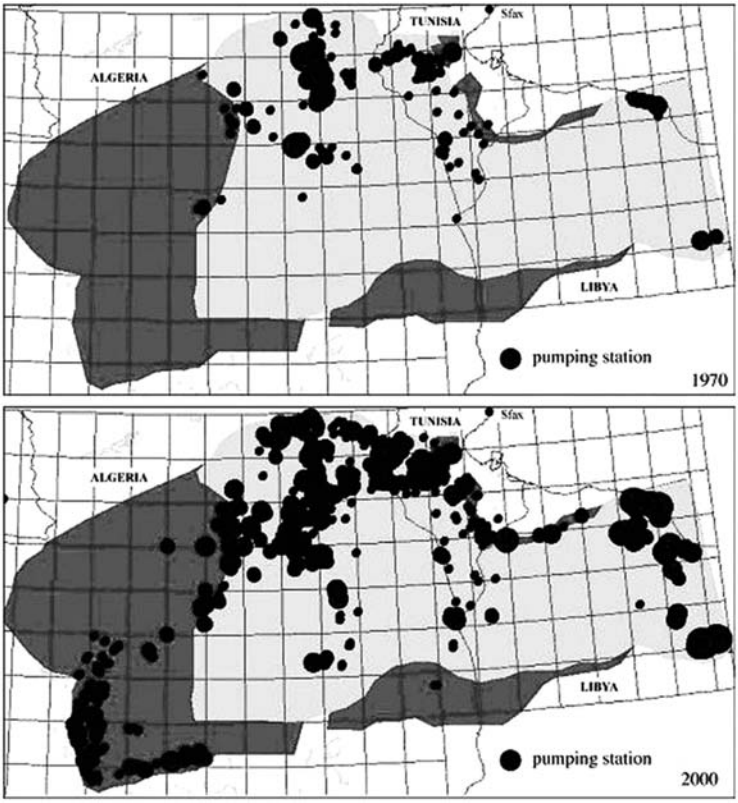

Fig. 6.3 Evolution of pumping in deep aquifers between 1970 and 2000 in southern Algeria, Tunisia, and Libya. (Source: Latrèche 2003)

6.2.4 Desalination of Seawater

The threat of lack of water led governments to consider alternatives to freshwater. To varying degrees, all the Maghrebian countries embraced desalinization as an option (see Chapters 15 and 19). Algeria has chosen a perennial solution. The Public Corporation of Water (EPAE) has built 23 seawater desalinization plants as part of an emergency program adopted by the Algerian government in 2002 to tackle the country's water shortage. In the northwestern part of the country where the shortages are the most serious, the mobilization of groundwater reached its maximum threshold. As a result, water tables were over-exploited and water quality decreased. Fourteen stations with a capacity of 1,940,000 m^3 per day are under construction and fall under different systems of management (i.e., private/public participation). Several other stations are under development.

In Tunisia, the National Company of Exploitation and Distribution of Water (SONEDE) has stressed that "the desalination of sea water [sic] represents the most economic alternative to meet the additional requirements of water for the area. This project will be brought into service in 2009." The strategy implemented by SONEDE to reinforce water resources and improve drinkable water quality—particularly in the long term—involves desalinizing seawater to meet demand in the arid regions, especially in the governorates of Médenine and Gabès, by building a station with a capacity of 50,000 m^3 per day. A station is already functioning on Kerkennah Island, and the construction of three seawater desalinization units, each having a capacity of 50,000 m^3 per day by 2015, is planned in Sfax. To ensure the operation of these stations, one has recourse to renewable energies. Moreover, SONEDE must also reduce the salinity of the water distributed throughout the country; to do this, 10 water desalination stations will be installed and will have a capacity of 30,000 m^3 per day in the southern zones, including Kébili, Douz, Tozeur, and Nefta. In Tunisia, the salinity of water is a challenge because 50% of the usable water resources have a salinity rate of 1.5 gram/liter (g/L), especially "in the south of the country where water of good quality is rare," according to the local director of desalination and the environment. To stabilize the water supply of the island of Jerba until 2025, SONEDE plans to install a desalination station with a capacity of 50,000 m^3 per day.

In Libya, the public and private sector agencies have invested in tapping groundwater through the Great Man-made River (GRA) project and the desalination of seawater. The GRA began in 1983, and the construction of the pipeline and viaduct system is now nearly complete (2008). Water totaling 2 billion km^3 per year must be transferred by two enormous pipes. The first takes water nearly 1,000 km from the sandstone aquifer of Nubie (Koufra, Tazerzou, and Sarir) towards the Benghazi area. The second pipeline, completed in 1996, leads water to Tripoli from the groundwaters of Mourzouk in Fezzan. The cost of this work is enormous: more than $30 billion. Experts worry about the environmental consequences of this project and the risks of exploiting nonrenewable resources on such a scale. In addition to the GRA, 40 desalination stations are under construction or are operating (Janzour, west of Tripoli, with 80,000 m^3 per year; Khoms, which is in development; and the quasi-functional Tobrouk station in the east of Benghazi). Libya hopes to double its capacities for treatment by 2025.

In Morocco, the desalination of seawater has become increasingly inevitable for the southern zones of the country despite its relatively high cost. Since 1976, 44 units have been installed. To help reduce the amount of energy consumed by seawater desalinization, the National Office for Drinking Water (ONEP) conducts feasibility studies and tests the use of various forms of energy, including wind and nuclear energy, to find the most technically and economically advantageous solutions. ONEP is working with private companies to implement complete high-pressure pumping stations which would, in the long term, make it possible to reduce energy consumption by almost 50%.

The energy costs of such techniques are a crucial issue for all these Maghreb countries. Such feasibility studies are available for all the countries, but Morocco—the only non-oil producer—must find a new type of energy that is more advantageous than the systems available today.

6.2.5 Recycling

The region is important for understanding the role of culture in water management. Nearly 99% of the population is Muslim, and opposition to the use of "soiled water" has somewhat delayed the efforts to recycle wastewater. Tunisia and Morocco already recycle a portion of their wastewater (200 million m^3 per year in 2002 in Tunisia), especially for agricultural use. Recycling is used only on a limited number of parcels located around main cities and for specific crops that are managed by the government with special recommendations. In addition, rainwater runoff should be reused after treatment in all the Maghrebian countries. Algeria and Libya launched projects in this direction and are convinced that these techniques can provide a solution for industry, urban water use, and especially agriculture; the amount of agricultural land irrigated with recycled water increased in the last four decades by 150–200%.

6.3 Water Resources Management

In today's Maghreb, the water supply situation is rather alarming because the availability of freshwater averages only about 1,000 m^3 per inhabitant per year. This figure will decrease, according to different scenarios, to less than 500 m^3 per inhabitant per year in 2025. The demand for water is increasing in households, agriculture, industry, and every other sector. In these very fragile zones, the use of water resources is not managed in a rigorous way.

Standing at 22 million in 1950, the Maghrebian population has more than tripled in half a century (Fig. 6.4). Today, the region is home to more than 75 million inhabitants, and demand for water has multiplied sevenfold. By 2025, the four countries will have 120–130 million inhabitants—10 times greater than the population of the region in 1920. This demographic explosion is one of the most pronounced in the world, with growth rates of about 2.7%. The region is characterized today by large metropolises: in 2005, the population living in urban areas of more than 750,000 people totaled 4.20 million in Algeria, 3.41 million in Libya, 6.73 million

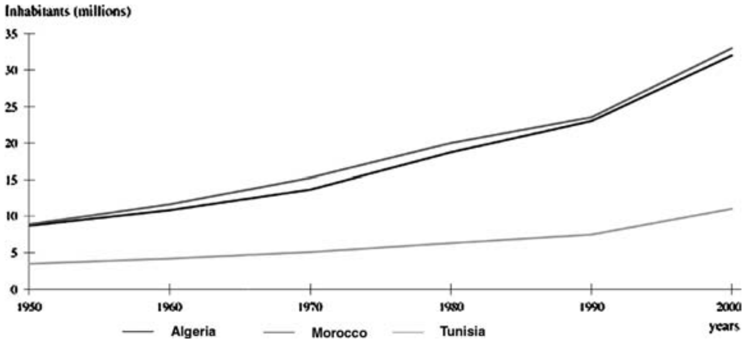

Fig. 6.4 Evolution of the population in Maghreb between 1950 and 2000

in Morocco, and 1.81 million in Tunisia (Population Reference Bureau 2008). The total population of each country in 2008 was 34.70 million in Algeria, 6.28 million in Libya, 31.18 million in Morocco, and 10.34 million in Tunisia (Population Reference Bureau 2008).

Several cities are experiencing problems due to water shortages. In Algeria, these shortages have prompted citizen protests in some areas, including west of Algiers, Abadla, and Skikda (Amzert 2009). Cities also face water rationing. The distribution is available one day out of two at most in the majority of Algerian cities. In Libya, all houses are equipped with an individual reservoir, and in central Tunisia, a majel, a reservoir under the house, stocks rain water.

Despite the differences in the various Maghreb countries, water demand remains strong. On average, water is allocated to various sectors: 82% for agriculture, 13% for drinking water, and 5% for industry (Bouguerra 2001). Agriculture is the primary user, and agricultural areas are expanding. In Tunisia, areas of irrigation increased from 65,000 ha in 1956 to 145,000 ha in 1975 to approximately 345,000 ha today. The other countries have seen similar increases; hectares of irrigated land have increased by more than 150% in Algeria, 290% in Libya, and 45% in Morocco (Mutin 2000). In Morocco, more than 80% of the water resources are used in agriculture.

In the steppe areas, overgrazing is a problem because stockbreeders continue to increase their livestock, create new agricultural spaces, and dig wells. Figure 6.5 indicates the close relationships between the progressive evolution of the population, livestock, and the reduction in rainfall in the Algerian steppe areas (Nedjraoui et al. 2006). The population is growing, and the tendency to sedentary farming is seen in an increase in the land cultivated.[6] The exponential growth of livestock is

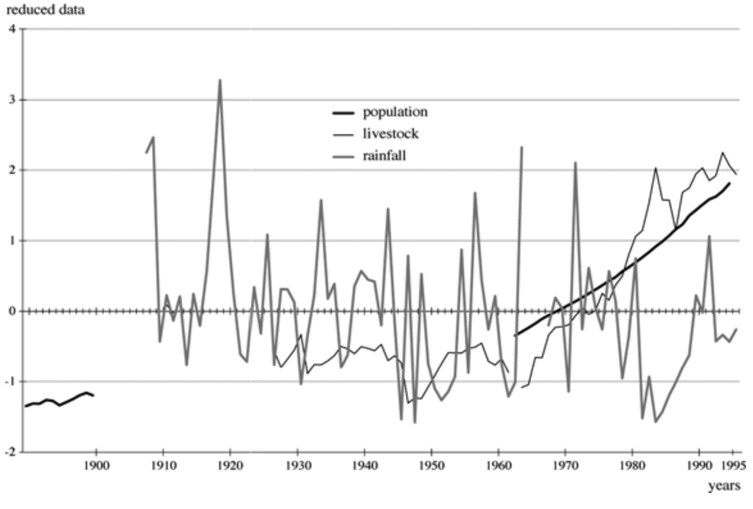

Fig. 6.5 Evolution of population, livestock, and rainfall in the steppe of Algeria. (Source: Nejraoui et al. 2006)

perceptible, while the tendency to aridity can be seen in an 18–27% reduction in rainfall and a two-month extension of the dry season during one century (URBT 1978; Aidoud 1991; Djellouli 1996). Policies designed to organize the steppe areas have failed for several reasons: the inadequacy of the Pastoral Code; the disrespect of tribal territories, and a lack of coordination and dialogue between stakeholders. In addition, in central and southern Tunisia, the agricultural policy encouraged the populations to stabilize and transform pastoral land into agricultural territories by introducing irrigated crops, particularly olive groves (Djellouli and Daoud 2002). These very fragile arid regions are subject to water and wind erosion, recurring dryness, and an increasingly strong anthropic pressure, which leads to changes in the level of the ecosystems' biomass and biodiversity (Djellouli 1996). These changes induce modifications in the status of the lands and thus the social and economic development of these arid regions.

6.3.1 Water Collection and Distribution

The Maghrebian countries inherited from their colonial past—and continued to develop—large hydraulic infrastructure for collecting and storing available water. This traditional engineering model of water management is at stake today, as it is expensive and poses economic, technical, and environmental problems. More recently, while a dominant trend of building great hydraulic installations exists, parallel trends of building smaller structures have emerged.

6.3.1.1 Dams

In Algeria, the Dams National Agency (ANB) is using 50 dams with a capacity of 5.1 billion m^3. Sixteen dams with a capacity of 2.3 billion m^3 are under construction. Four other dams are part of a project within the special framework emergency program to reinforce the drinking water supply in large cities. Full capacity represents more than 10.5 billion m^3 by 2012 with a capital budget of 276 billion Algerian dinars (approximately 2.7 billion Euros) and an annual operating budget of 388 million Algerian dinars (approximately 3.9 million Euros). The ANB hopes by 2012 to double the mobilized capacity and manage a stable and regularized volume.

In Libya, shaabiyates (districts) support the construction of the dams, water tanks, and reservoirs. Today, 17 dams exist with a capacity of 60 million m^3 per year, and officials envision building 23 new dams with a storage capacity of 120 million m^3 of water per year.

The transfer of water is at the core of hydraulic policy in Tunisia. During the 1980s, the Decennial Strategy of Mobilization of Water Resources was established to mobilize nearly all of the available resources within acceptable limits of quality and costs (Fig. 6.6). To achieve these goals, the strategy proposed the construction of 21 dams and many other works, including colinary lakes (artificial reservoirs for agriculture, irrigation, and other activities), structures for spreading

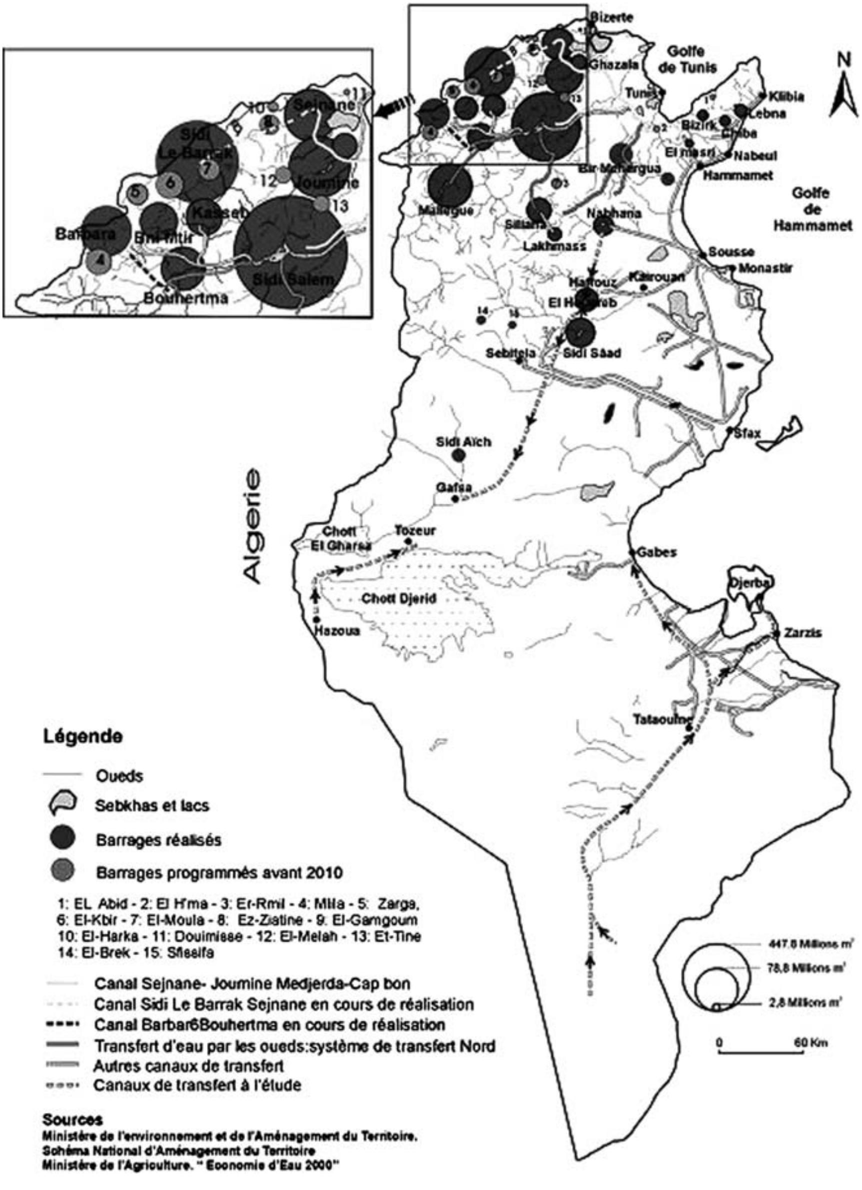

Fig. 6.6 Mobilization and transfer of water in Tunisia. (Source: Daoud 2004)

and artificially refilling the groundwater tables, new and replacement drillings, and treatment plants. In 2000, the Ministry for Agriculture estimated the completion rate at 70%. This strategy defined the role of small hydraulic projects in the mobilization of water.

In Morocco, much effort has been deployed to study and develop hydraulic infrastructure, and 110 dams have been built. Storage capacity grew from 2.3 billion m^3 in 1967 to 16 billion m^3 in 2004. Dams often play a double role in energy production and irrigation. Standing 130 m tall, the Bin el Ouidane dam is the largest dam in Morocco. In terms of energy production, it has a capacity of 1,384 hm^3, irrigates 69,500 ha, and produces 287 gigawatt hours (GWh) of electricity.

6.3.1.2 Colinary Lakes

"Each drop of rain which falls should be used instead of joining the sea" is the guiding principle of the Water and Soil Conservation Program in Tunisia. In an effort to save water, 640 colinary lakes were built in the country between 1990 and 2000. The lakes helped improve agricultural production, which accounts for 17% of the gross national product, according to the Food and Agriculture Organization (FAO).

In Algeria, six projects within the framework of the national program were launched in 2002 in arid and semiarid regions: M'Sila (Bounesroune and Ced Fella), Djelfa (Hadjia and Toughoursène), and Oum El Bouaghi (Hammimet and Ourkis). A cooperative program between Cuba and Algeria provides assistance to regional management structures.

6.3.1.3 Rainwater Collection

Rainwater collection is used in arid regions of the Maghreb. A rainwater collection project was adopted successfully in Tunisia, within the framework of a partnership with Italy. Indeed, during the last two decades, the Tunisian authorities made considerable efforts to rehabilitate soils that are subject to water erosion and to intercept surface waters. Participation from the local population is essential to the success of the project. In fact, the farmers take part in this program by building thousands of small individual basins and terraces to collect rainwater before it is lost to the natural discharge system. Currently, the farmers endure the severe climatic conditions—nearly four consecutive years with a rainfall deficit—and the consequent migration towards the cities. However, some others hope for better days, with the installation of infrastructure, financial support, and training on improved agricultural methods.

A water and soil conservation program (co-financed by bilateral and international assistance) supports the efforts made by the government of Tunisia to regenerate the arid soils and has shown encouraging results. Regenerating the arid soils to make these spaces prosperous is important in stabilizing the population. Agricultural development set up in the governorates of Kairouan and Zaghouan is based on a participative and integrated approach with the local practices and the local economy that takes into account local aspirations. These include cultivating the olive tree while safeguarding traditional varieties and using natural fertilizers in the basin. In addition, the olive tree retains the surface waters better than cereals and renders more service because its leaves are used as fodder and its wood as fuel.

6.3.2 Reuse of the Foggara/Khettara

In the hyperarid zones, several traditional techniques are used to irrigate oases. The ingenious qanat system of tunnels and wells originated in Persia and was introduced to the Maghreb during the Arab conquest in the seventh century AD. Known as a khettara in Morocco and foggara in other parts of North Africa, the system collects groundwater and carries it through small tunnels to irrigate lower-lying areas (see Chapters 8 and 10). There is however, a tendency for the inhabitants of the oases to overlook their traditional knowledge and pump out the subterranean water from great depths and in large quantities, a practice that drains the water table, often in an irreversible way. While these foggara/khettara systems have a limited impact at the national level, they are important for local populations of oases. Many officials and nongovernmental organizations recommend rehabilitation of this system. The Touiza community association and MED Forum (the Network of Mediterranean NGOs for Ecology and Sustainable Development) are helping rehabilitate, repair, and monitor foggara systems in the oases of the Algerian south (Adrar) to promote conservation and sustainable development of these lands, stabilize the populations of the oases, and reduce poverty and desertification.

6.4 The Water Agenda

One of the largest challenges for the Maghreb in the twenty-first century is to find sustainable solutions for the problem of water scarcity. This will require agreements between stakeholders of drinking water, agriculture, industry, tourism, etc. The demand for drinking water and irrigation spiked during the twentieth century, while pollution of the aquifers reduced hydrological reserves. Existing drinking water resources, however, could be used much more effectively by recycling, maintaining water networks, and reducing wastewater. Efficiency in agricultural water can be achieved by growing crops that require less water and are more salt tolerant and reducing contamination and evaporation of reservoirs. Alternative technological and new management approaches have to be introduced; for example, to minimize evaporation losses, surplus waters could be injected into aquifers (see Chapter 14).

Due to different geographical conditions, equity of access to water—an objective of national solidarity—will require the transfer of water, sometimes as far as 1,000 km, from areas of abundance towards areas less well endowed—for example, from the Sebou watershed (eastern Morocco) to Casablanca; the Isser watershed to Algiers; the Medjerda watershed to Sfax; and the Koufra watershed to Benghazi. This will require huge investment in new infrastructure.

As in other arid countries, water managers are sharing ideas and learning through the experiences of others. But an absolutely essential part of the process involves empowering civil society and the private sector to apply integrated management of water resources together, in partnership, which requires the simultaneous application of technical, economic, financial, and institutional approaches (Sciences de la société 2005). In agriculture, the major water user, cropping plans and irrigation practices based on the economic use of water must be encouraged. Solutions must include unconventional resources and the gradual integration of education, improved water management, and technology to change society's way of thinking about water in such arid regions of the world as the Maghreb.

Notes

1. The data on which we worked come from several sources. Even if there are sometimes differences in the figures, we tried to be as close as possible to reality by consulting several sources (e.g. OSS/Margat 2001; Pèrennes 1993; IWMI 2000; Moksit 2000; ANRH 2001; Daoud 2004; ONM 2005).
2. The figures presented here are slightly different from those of the World Forum of The Hague in 2000 for the "Vision of the water usable resources" by IWMI (International Water Management Institute) 2000. The PUF (Potential Utilization Factor) was added.
3. Wadi is an Arabic word used to describe rivers.
4. Based on the author's research, 2005.
5. Albian refers to a stage of the Cretaceous period, between about 112 and 99.6 million years ago.
6. Based on author's field investigations.

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Chapter 7
Changing Water Resources and Food Supply in Arid Zones: Tunisia

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and Ghislain De Marsily

Abstract The notion of water security in an arid country takes on another dimension when the comprehensive water balance concept is applied to water used by rain-fed agriculture and to the water equivalent of international food exchanges. In the case of Tunisia, this concept expands the prospects for improvements in national food security by optimizing the food balance and the corresponding virtual water flux. It also prompts reconsideration of criteria and indicators classically used to characterize water stress situations. The current situation shows that about 30% of the water used in Tunisia is imported as food (virtual water); that number is likely to reach 40–50% in 2025 due to climate change, diet change, demographic growth, and improved water management. Asia and North Africa will most likely not be self-sufficient in terms of food production and will need to import food from other continents (e.g., South America). Africa, however, could be self-sufficient if its existing water resources are developed. Bioenergy production is likely to be limited to a small fraction of the global energy needs. Major food shortages in cases of severe global droughts (e.g., during very strong El Niño events) may occur, however, with severe consequences in terms of food availability.

Keywords Climate change · Droughts · Food production · Tunisia · Virtual water

7.1 Water Resource Planning and Management in Tunisia

Tunisia is well suited to a discussion about how water resources in an arid area are interlinked at the national scale because it is fairly advanced in water resource planning and management, and its scarce hydraulic resources are almost entirely mobilized. The country is therefore obliged to apply new concepts and paradigms, to optimize the use of different types of water resources, and to change the behavior of some parts of the population (Chahed et al. 2005, 2007; Besbes et al. 2007).

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G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
DOI 10.1007/978-90-481-2776-4_7,

Generally, the main water resource management objective is to provide sufficient quantities to municipalities, industry, and agriculture by developing blue water—surface water and groundwater. In arid countries where water resources are scarce and where the economy and the population are developing, the water needs increase and additional withdrawals are starting to pose problems. The urban and industrial needs, the so-called direct water demand, depend on the standard of living but remain moderate compared to the large quantities of agricultural water (irrigated and rain-fed agriculture) known as green water and used in food production. When local water resources are insufficient to guarantee the food production that the population needs, food imports—known as virtual water—are required to fill the water deficit (Allan 1998; Renault and Wallender 2000; Hoekstra 2003; Oki et al. 2002) (see Chapters 13 and 19).

7.2 A Vulnerable System Under Intensive Surveillance

Tunisia is situated in North Africa and is bordered by Algeria, Libya, the Mediterranean Sea, and the Sahara. The country has a surface area of 164,420 km^2 and 10 million inhabitants. The average rainfall is 220 mm/yr, which translates into a rainfall resource of 36 km^3/yr. Total hydraulic resources (blue water) are estimated at 4.85 km^3/yr. The mean runoff is 2.7 km^3/yr, of which 2.1 km^3/yr can be exploited through dams. Exploitable groundwater resources are estimated at 2.15 km^3/yr. In 2006, groundwater abstraction was estimated to be 1.95 km^3, which represents an exploitation index of 90%. The soil water resource, which is part of the rainfall resource infiltrated into the soil and available for evaporation and consumption by plants, refers to the arable land (5 million hectares, or ha) and is estimated at 12 km^3/yr, the country's total green water potential.

The total water withdrawals reached 2.64 km^3 in 2006; 0.4 km^3 of that was allocated for drinking water and 2.1 km^3 for irrigation. Of the irrigation water, 75% comes from groundwater, 23% from surface water, and 2% from reuse of treated wastewater. The area that can potentially be irrigated is estimated at 560,000 ha. Most of the demand is concentrated in the populated coastal zones, and some of the main irrigated areas are situated far from the wettest parts of the country. The coastal zones therefore use more water than they receive in rainfall and inflows, obliging them to import water. The whole country is now marked by major west–east water transfers. This situation requires tremendous resource monitoring efforts: the rainfall monitoring network is composed of more than 900 regular rain gauges; the runoff network consists of 60 permanent stations and 60 points of regular measurements; and the regular groundwater observation network is made up of 3,800 points. This constantly updated information allows the authorities to review their resource assessments regularly, focusing mainly on groundwater, as exploitation of that resource has increased by 250% in the past 40 years. Groundwater pumping, mainly for agriculture, now reaches 90% of sustainable levels, creating great risks to the quality of the resource itself. The government has deployed a number of measures in its efforts to preserve water resources and provide farmers with incentives to optimize their consumption. For example, in 2005, 75% of the total irrigated area, which represents 400,000 ha, was equipped with water-saving devices such as drip and sprinkler irrigation and modern surface irrigation methods because farmers have responded to financial incentives from the government.

Large-scale hydraulic programs make the water cycle strongly artificial, which leads to a reduction of the water that feeds natural hydrologic systems, with consequences for the behavior of continental and coastal aquatic ecosystems; a reduction of recharge to aquifers situated downstream of large dams; and a progressive salinization of soils irrigated with highly saline water. In these conditions, the protection of the environment and resources requires a continuous assessment of the environmental water demand. In the planning of water allowances, artificial floods for wetlands and groundwater recharge or additional irrigation shares to prevent salinization of irrigated soils should be included. Increased irrigation shares for salt leaching in soils were applied early on, whereas the understanding of other environmental needs requiring a direct water allowance from mobilized resources has been progressive and now has become an essential component of water resource planning and management. On a national level, the environmental water demand remains small compared to the urban and agricultural requirements, but it represents a growing concern in the planning of future hydraulic programs.

7.3 Food Security, Food Trade, and Virtual Water

Tunisia's food security goals are to satisfy, to the greatest extent possible, the country's basic food needs (cereals, oil, meat, milk, etc.). However, Tunisia is not self-sufficient in some of these products. Most importantly, climate variations cause large fluctuations in the yield from rain-fed agriculture (Besbes et al. 2008). The food trade balance of Tunisia has been negative during the last two decades, except for the rainy years of 1991, 1999, and 2004. This balance (Figs. 7.1 and 7.2) depends strongly on cereal imports, which represent close to 45% of the total value of food commodities imports.

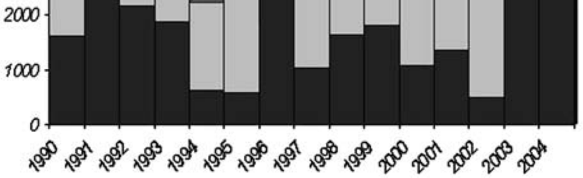


Fig. 7.1 National cereal production and imports in Tunisia from 1990 to 2004, in 10^3 tons. Source: MARH 1995 to 2004

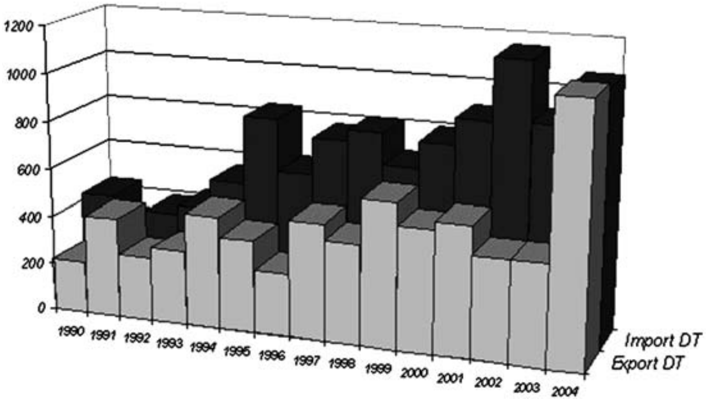


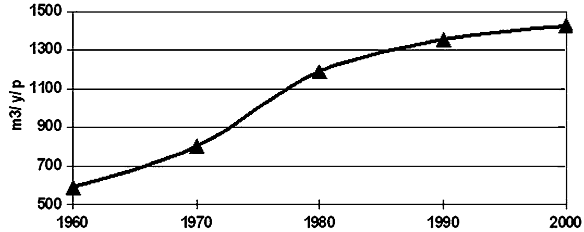
Fig. 7.2 Food imports and exports, 10^6 Tunisian dinars, 1990 to 2004 (1 Tunisian dinar ~0.84 US $ in July 2008) *Light gray*: export. *Dark gray*: import

The direct water needs, which include municipalities, industry, and tourism, are small compared to the agricultural demand. The concept of virtual water—the quantity of water needed to produce a given type of product—can help in the analysis of the relationship between agriculture and water resources. Based on production and trade statistics of food products, one can establish the national budget of water demand in Tunisia (Table 7.1). In an average rainfall year, half of the water required to meet Tunisian food needs is provided by rain-fed agriculture, one-sixth by irrigated agriculture, and almost one-third by virtual water in the form of imported food. Tunisia imports the water equivalent of 5.2 km^3/yr, essentially in the form of cereals, and exports agricultural products such as citrus fruit, dates, olive oil, and early season produce equivalent to 1.5 km^3/yr for an average annual deficit of 3.7 km^3/yr (Chahed et al. 2007).

Table 7.1 Comprehensive water demand of Tunisia (average values for 1990–1997)

Sector	Water demand, billion m^3/year
Irrigation	2.1
Rainfed agriculture	6.0
Deficit of food balance [imported virtual water]	3.7
Urban	0.4
Industry	0.1
Forests and rangelands	5.5
Water bank [storage in dams for droughts]	0.6
Environment [conservation of humid areas]	0.1
Total water demand	18.5

Fig. 7.3 Evolution of per capita water equivalent of the Tunisian food demand during the last 40 years.



The current water deficit is likely to increase in the future because food requirements and the population's tastes evolve and the pressure on the resource restricts domestic production. Food demand can evolve quickly because of improved living standards. The per capita water equivalent of Tunisian food demand (1,400 m^3/yr) has more than doubled over the last 40 years (Fig. 7.3) and will probably continue to increase in future decades. The implications for agriculture and the food-trade balance are considerable, especially as the nature of the exchanged products may fluctuate as markets evolve and agricultural policies are modified.

7.4 Factors of Change and the Comprehensive Water Balance Model

Demographic, social, and economic factors will determine the future demand and availability of water resources. After the strong demographic growth of the second half of the twentieth century, the Tunisian population is now reducing its growth rate and will stabilize at about 13 million inhabitants by 2050 (Institut National des Statistiques 2005). Industrial development and urbanization will also have strong impacts on water resources, including an increase in the per capita drinking water requirements and water quality standards, as well as changes in the population's diet. In addition to this evolution, the risks to the resources are multiple: groundwater over-exploitation, increased water and soil salinity, urban and industrial pollution, etc. The major problem, however, is the management, a few years hence, of a situation in which 100% of the resources will be mobilized, and all technical, economical, and institutional preservation measures will have been applied while the population and the per capita needs of the Tunisians continues to rise. How can the water security of the country be guaranteed under these conditions?

One can start with a certain number of observations. The first one is that rainfed agriculture plays an essential role in food security; it represents, in an average hydrologic year and with average monetary values, 65% of the national agricultural production and 80% of the agricultural exports. The second observation is that water security comes down to a food security problem: (a) the largest share of the mobilized resource (blue water) is used in irrigation, (b) the blue water exploitable resource stabilizes, (c) the direct demand (drinking water, industry) is incompressible and increases with the population, and (d) consequently, the blue water agricultural allowances should necessarily decrease.

The comprehensive water balance model constructed by Chahed et al. (2007) shows that the water allocated to irrigation is the quantity of blue water available when the direct water demand has been satisfied (equation 7.1). The model also demonstrates that virtual water expresses the balance of the water equivalent of the food needs, the water equivalent of green water, and the water equivalent of the irrigated agricultural production (equation 7.2).

$$IW = EWR - (1 - RI)_* DD \tag{7.1}$$

$$VW = FDWE - GW - k_* EWR + k_* (1 - RI)_* DD \tag{7.2}$$

IW	*Irrigation water volume*
EWR	*Exploitable water resource*
RI	*Recycling index*
DD	*Direct demand*
VW	*Virtual water volume*
FDWE	*Food demand water equivalent*
GW	*Green water volume*
k	*Irrigation factor (Converts irrigation volumes into water equivalent of the irrigated food production; this factor integrates irrigation efficiency and rainfall contribution).*

The verification of this model consists of testing a certain number of values of the parameters k (the irrigation efficiency factor) and RI (the recycling index for the direct demand), while providing the data concerning EWR (exploitable water resource), DD (direct demand), and FDWE (food demand water equivalent), and calculating the reference variable, VW (virtual water volume). The validation of the model on the situations of 1996 and 2004 is summarized in Table 7.2.

The calculated virtual water corresponds well to the observed import–export balance, which is a good validation. It is necessary to keep in mind, however, that this model is strongly constrained because the total food demand has already been estimated by the import–export balance; it is therefore not possible to do any further calibration of the model but simply to verify the consistency of its results. The model is very useful for running simulation scenarios. For example, from 1960 to 2000, the per capita food demand water equivalent increased from 1,200 to 1,600 m^3/yr in Europe and from 600 to 1,400 m^3/yr in Tunisia during the same period. The projection to 2025 of the Tunisian per capita food demand, expressed by continuing the trend of the last years, would be 1,700 m^3/yr.

Using the comprehensive balance model, the first simulation for 2025 maintains the present situation, except for the population variation. All other elements are kept at their 2004 level: food demand, direct demand, recycling index, global irrigation efficiency, and the rain-fed sector production. As a result, the virtual water necessary

Table 7.2 Validation and scenarios in the comprehensive balance model

	Units	1996	2004	2025 Simulation N°1	2025 Simulation N°2	2025 Simulation N°3
Population	10^6 persons	9.10	9.93	12.15	12.15	12.15
Exploitable water resource, EWR	10^6 m^3/yr	2,380	2,500	2,700	2,700	2,700
Food demand water equivalent, specific	m^3/yr	1,350	1,450	1,450	1,700	1,700
Food demand water equivalent, total, FDW	10^6 m^3/yr	12,285	14,399	17,618	20,655	20,655
Direct demand, specific	m^3/yr	45	55	55	70	70
Direct demand, total, DD	10^6 m^3/yr	410	546	668	851	851
Recycling index, RI	–	0.08	0.1	0.1	0.5	0.5
Irrigation water volume, IW	10^6 m^3/yr	2,003	2,008	2,099	2,275	2,275
Green water volume, GW	10^6 m^3/yr	6,500	8,000	8,000	8,000	10,000
Irrigation factor, k	–	0.9	0.9	0.9	0.9	0.9
Virtual water volume, VW	10^6 m^3/yr	3,982	4,591	7,729	10,608	8,608
Total use	10^6 m^3/yr	12,695	14,945	18,286	21,506	21,506
Water dependancy index	–	31%	31%	42%	49%	40%

to close the budget gap increases from 4 to 7.6 km^3/yr, and the water dependency index exceeds 40% (Table 7.2). The second simulation for 2025 corresponds to the increased living standard tendency. This scenario prolongs the tendencies of the per capita food demand, which rises to 1,700 m^3/yr; the direct per capita demand, which reaches 70 m^3/yr; and recycling. In this case, the virtual water increases to 10 km^3/yr, and the water dependency index approaches 50%. In the third simulation, the productivity of the rain-fed agricultural sector is assumed to grow very strongly, with a gain of 25%. This would make it possible to reduce the virtual water to the first scenario level.

The financial parameters that are not integrated into the model could greatly influence the results. For example, the balances and performances of the Tunisian food trade observed until now were in part possible because the price of wheat has remained fairly steady and low for a relatively long period. International cereal prices have remained low because of the state-controlled subsidies in the main producer countries and remarkable yields due to intensive use of chemical fertilizers. However, recent upheavals in cereal prices demonstrate that the situation can change suddenly and can dramatically influence the world food trade balances.

The Tunisian example illustrates how blue water, green water, and virtual water are interlinked and constitute the entirety of the water cycle at a national scale, and how this general analysis acquires a particular and timely relevance in countries that have limited water resources and have mobilized a large share of their resources. This aspect of the issue should call into question certain established concepts, such as the definition of water resources, water stress, water policies, integrated water resource management, and demand management.

Four additional external factors can further influence the water balance of countries like Tunisia, as described above, given the more general problem of the water resources on Earth: climate change, food availability on the global market, human diet, and food production efficiency.

7.5 Climate Change

At present, it is overwhelmingly agreed that greenhouse gas (GHG) emissions are responsible for the accelerating climate change. The review conducted by the Académie des Sciences (2006) concluded that the effects of climate change for the next century are fairly well predicted as far as temperature is concerned, depending, of course, on the GHG emission scenario. The hydrologic effects are much more uncertain. Nevertheless, the current prediction is that the temperature increase will generate a significant acceleration of the water cycle, with more evaporation and an increase in the amount of water vapor present in the troposphere, while the relative humidity will remain more or less constant. The global rainfall will thus increase, but its spatial distribution is much more uncertain. Figure 7.4 shows the

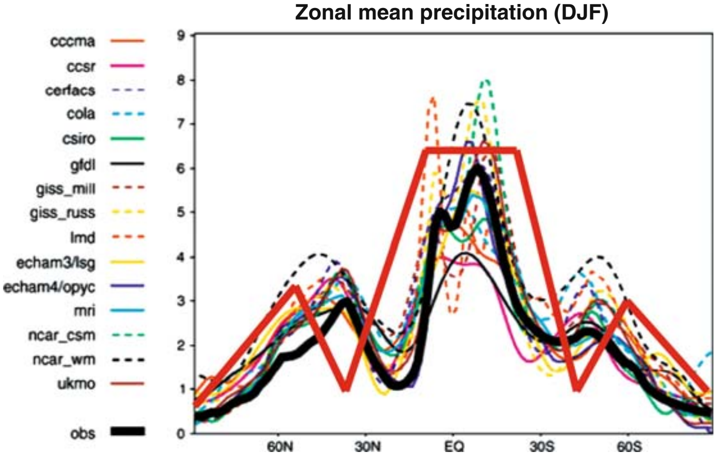


Fig. 7.4 Mean zonal precipitation (mm/day) for December, January, and February for the current climate, observed (*bold black line*), and calculated with 15 models. The *thick gray line* is a schematic representation of the precipitation changes for the climate towards the end of the century (Adapted from Lambert & Boer 2001)

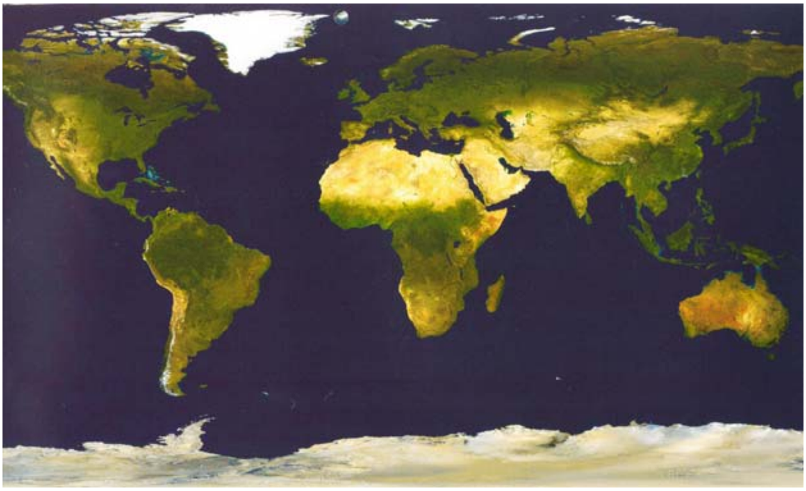


Fig. 7.5 Dry areas of the world today (See also Plate 9 on p. 340 in the color plate section)

zonal distribution of average rainfall (from pole to pole) for the current climate, as measured (thick black line) and as calculated for the present time with 15 different climate models. A large variability between models can be observed, which partly explains why the model predictions of rainfall for future climates are so uncertain.

The expected general consequences of climate change are a shift towards the poles of the climate zones, as shown by the schematic thick grey line in Figure 7.4. The dry areas of the world, as shown in Figure 7.5, would move towards the north in the Northern Hemisphere and towards the south in the Southern Hemisphere. At the same time, the upper latitudes and the tropics would receive more rain.

Figure 7.6 shows the precipitation changes (in millimeters per day and percent) from the second half of the twentieth century to the second half of the twenty-first century, for December to March and June to September, calculated by the Météo-France model from the Centre National de Recherches Météorologiques for the International Panel on Climate Change (IPCC) scenario B2 (Académie des Sciences 2006). The same results supplied by the latest IPCC report (2007) from an average of different models are very consistent with the preceding ones.

Apart from the average precipitation changes, the issue of climate variability was also considered by the Académie des Sciences (2006) and IPCC (2007). The probability of occurrence of the annual rainfall can be described by its distribution function. Climatologists agree that if the average annual rainfall increases, it is most likely that the whole probability distribution will shift towards an increase. In that case, the probability of floods will increase and that of droughts will decrease. The opposite would be true if the average rainfall decreases. What is not known, however, is whether the shift of the mean will also affect the distribution and modify, for instance, its variance. In that case, the probability of both floods and droughts could increase, whatever the change in the mean. The latest IPCC report (WG1,

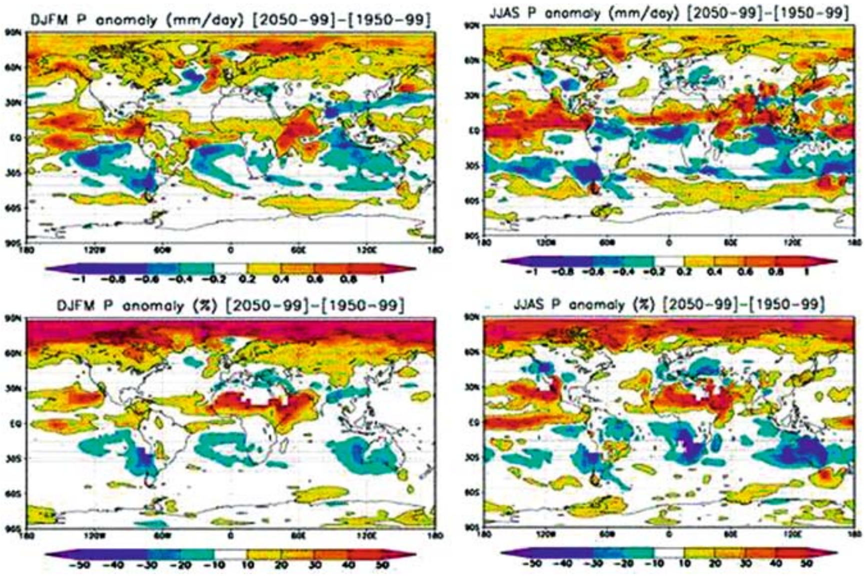


Fig. 7.6 Precipitation anomalies (*top*: mm/day, *bottom*: %) calculated for the IPCC B2 scenario with the French CNRM model, comparing the averages for 1950–1999 and 2050–2099. *Left*: for December–March. *Right*: for June–September. (Source: Académie des Sciences 2006) (See also Plate 10 on p. 341 in the color plate section)

Chapter 3, 2007) indicates that, based on observations, an increase in the variability of the climate seems indeed likely (i.e., both a shift in the distribution and a change of the variance toward more variability). Unfortunately, current climate models are unable to answer this question; only observations can be used to infer the changes, but they obviously require long time series.

These changes are, as explained before, quite uncertain, and might perhaps occur earlier than the second half of this century. The major expected consequences for the water resources distribution in the world include the following:

For southern Europe, Mediterranean-latitude zones, South America, and southern Australia

- a large decrease, on average, of soil water content (higher evapotranspiration due to temperature increase and lower rainfall, particularly in summer); a decrease of rain-fed agricultural production;
- an increased risk of agricultural droughts, which occur during the spring and summer months and mostly affect vegetation;
- an increased risk of hydrologic droughts, which occur in the fall and winter and affect the recharge of aquifers and therefore the flow of rivers the rest of the time; however, this risk is probably lower than that of agricultural droughts because rainfall reduction occurs mostly in summer months;

- an increased risk of floods; very intense rains are likely to occur more frequently;
- an increased risk of forest fires.

For northern Europe, northern Russia, northern America, and equatorial zones

- increased water resources, both in summer and winter;
- an increased risk of floods, particularly in winter;
- possible increase of droughts.

In general:

- ice melting in the Alps (and also in the Himalayas, the Andes, etc.) and on the polar cap edges (but perhaps an increase of ice at the poles, due to increased rainfall);
- warmer sea surface temperatures, likely to increase (in strength and/or frequency) hurricanes in the tropical zones;
- an increased frequency of El Niño–La Niña events; this is still debated but would mostly affect the monsoon zone;
- sea level rise (about 0.50 m in 2050, currently 3 mm/yr) from general warming of the seas (thermal expansion) and ice melting;
- a possible effect on the Gulf Stream is sometimes mentioned and would reduce the temperature in Europe; this is very uncertain and its timing is unknown, but it would not compensate for the general temperature increase.

For Tunisia, the most likely consequences of climate change seem thus to be a reduction of rainfall and an increase in the frequency of droughts, with rather severe effects on green water and blue water availability. Assuming a 10% reduction in both, and applying it to Simulation 3 for 2025 (Table 7.2), the virtual water import (food) would shift from approximately 8.6 km^3/yr (for a total of 21.5 km^3/yr and a water dependency index of 40%) to 9.9 km^3/yr and a water dependency index of ~46%.

The situation described above for Tunisia is likely to affect most of the current arid zones (Fig. 7.5). Figure 7.6 shows that rainfall decreases will unfortunately occur in most arid zones, at the desert belt latitudes, as they are the most affected by climate change, at least at their northern (for the Northern Hemisphere) or southern (for the Southern Hemisphere) limits. According to Viviroli et al. (2007), the desert zones cover roughly 18% of the world's surface and are home to 8% of the world's population. The semiarid zone and dry tropical forest represent 18% of the surface and 25% of the population. Keeping in mind the strong uncertainty of climate change predictions, one may, as a first guess, estimate that the situation likely to occur in Tunisia may therefore affect more than 20% of the world's population. The scenarios developed above for Tunisia with virtual water imports are viable solutions, provided food is available on the world market and at affordable prices. But where can food be produced, and will it be by rain-fed agriculture or irrigation?

7.6 Food Availability on the International Market

At the World scale, food production will be a major problem, not just because of climate change, but also because of demographic growth (Table 7.3). In 2050, it is expected that around nine billion people will live on Earth.

To produce the necessary additional food, arable land is required. Table 7.4 presents the surface area available for agriculture, per continent. A large increase of agricultural efficiency, both in rain-fed and irrigated areas, is needed but is not sufficient; fertilizers may become much more expensive, as nitrates are following oil prices and phosphate reserves may become depleted.

The current rate of increase of irrigated surfaces is 1.34 million hectares per year (Mha/yr); with 234 Mha of irrigated land in 2000, the irrigated surfaces would thus cover 331 Mha in 2050. This is insufficient to produce the amount of food necessary for nine billion people. Unless the present expansion rate of irrigated surface areas is multiplied by approximately 10, irrigation will not be able to provide the food needed by 2050; food production will depend on rain-fed agriculture in areas where

Table 7.3 Food needs in 2000 and estimated for 2050, in million tons per year (Mt/yr) equivalent cereals, taking into account diet changes and population growth

Regions	Asia	Latin America	West Asia North Africa	Sub-Saharan Africa	Countries of the OECD[1] and Russia and CIS[2]
Food need 2000	1,800	272	154	262	–
Food need 2050	4,150	520	390	1,350	Same as 2000
Food need multiplying factor	2.34	1.92	2.5	5.14	~1

Source: Griffon (2006): Collomb (1999)

1. OECD: Organisation for Economic Cooperation and Development
2. CIS: Commonwealth of Independent States (former Soviet Republics)

Table 7.4 Cultivated area in 2000 in million hectares (Mha) and area suitable for agriculture

Area	World	Asia	Latin America	West Asia and North Africa	Sub-Saharan Africa	Russia and CIS	OECD
Cultivated area (2000) (a)	1,600	439	203	86	228	387	265
Area suitable for agriculture (b)	4,152	585	1,066	99	1,031	874	497
a/b	39%	75%	19%	87%	22%	44%	53%

Source: FAO 2006, in Griffon 2006

Table 7.5 One possible scenario for food production (in Mt/yr) in 2050

Region	Asia	South America	West Asia and North Africa	Sub-Saharan Africa
Food production needed	4,150	520	390	1,350
Food production grown	3,190 ±100	1,704 ±100	166 ±10	1,350
Shortage/Surplus	–960 ±100	+1,184 ±100	–224 ±10	0

Source: Griffon 2006

land is still available—mainly South America and Africa. It is also clear from Tables 7.3 and 7.4 that some regions, in particular Asia and West Asia–North Africa—where the food multiplying factor is very large (around 2.5) and the population constitutes more than half of the World's total—do not have sufficient land to grow their own food: they already use 75% and 87% of the area suitable for agriculture, respectively.

Table 7.5 presents one possible scenario of food production that would meet the demand in 2050, after Griffon (2006). This scenario assumes significant technological changes to improve agricultural efficiency (+50% and +33% in rain-fed and irrigated agriculture, respectively) in Asia, Latin America, and sub-Saharan Africa; nominal investment in irrigation; and a major areal increase of rain-fed agriculture in sub-Saharan Africa and South America to compensate for the deficits in Asia and West Asia–North Africa that cannot be self-sufficient.

The distribution of cultivated land in 2050, assuming some land is used for energy production with the same food production scenario as above, is given in Table 7.6. According to this scenario, the cultivated area is projected to increase from 1.574 billion ha in 2000 (1.34 rain-fed + 0.234 irrigated) to 3.152 billion ha in 2050, with 2.587 billion ha for food production (2.174 rain-fed + 0.413 irrigated) and 0.565 billion ha for bioenergy production. Even if energy production is not

Table 7.6 Cultivated surface areas per continent in 2050 for food and energy production and remaining protected areas, in Mha

Area	Asia	South America	West Asia North Africa	Sub-Saharan Africa	OECD	Russia and CIS	Total
Area suitable for cropping	585	1,066	99	1,031	874	497	4,152
Protected areas	100	300	0	200	300	100	1,000
Area for food	460	646	99	711	424	247	2,587
Irrigated	250	26	49	17	24	47	413
Rain-fed	210	620	50	694	400	200	2,174
Area for energy	25	120	0	120	150	150	565

Source: Griffon 2006, with some numbers adapted from other sources included, feeding the planet will require increasing the cultivated area by 1 billion ha. The natural ecosystems will have decreased from 2.578 billion ha in 2000 to 1 billion ha in 2050, or 1.565 billion ha if there is no bioenergy production. In conclusion, water and climate change are not likely to be the limiting factors in controlling the current demographic growth of the planet. There will be enough land and water to produce the required food in normal years, but with enormous virtual water trade between continents[1] and a dramatic reduction of the biodiversity and natural ecosystems all over the world.

7.7 Virtual Water: Political and Economic Feasibility

As long as food production was in excess (and heavily subsidized) in the developed world, buying food on the World market was a feasible option and strongly encouraged by the United Nations, the World Bank, and other international organizations and agencies. Local food production was even discouraged and export crops encouraged. The recent food price crisis, with the wheat price rising from about $165 (US) per metric ton ($/t) to more than 400 $/t in a couple of years, has shown that cheap and easy procurement of food on the World market is no longer a reality. It is likely that many countries will now turn to food security by increasing their own food production. The increased food prices will make it possible for lower-efficiency crops (in terms of man-hour per ton) in the developing world to become economically feasible and to allow the farmers to survive, as most of the current poverty and malnutrition occur in rural communities. But in the longer term, food will remain in strong demand on the international market and food prices are likely to remain high. Emerging countries like Tunisia that have a strong economy, some mineral resources for export (mostly phosphates), and limited oil and gas resources will be able to pay the price of food. If food prices continue to increase and if energy costs increase less, it may even become economically feasible to use desalinized water for some high-yield crops, or rather to partly supplement local water resources through methods such as diluting slightly brackish water. But what about poor countries with no economic development or natural resources? The only option left is migration to less deprived areas, as has always been the case in the past when climatic or demographic conditions have changed. But where to go?

7.8 Drought

It is necessary to distinguish between local and global droughts. In case of a severe drought occurring in a country like Tunisia, but not over an entire continent, it is likely that the World food production will not be affected, or at least not significantly. The food deficit in one region will be compensated by food availability elsewhere and by existing stocks. In Tunisia, the government has established a set of drought management rules (Louati et al. 1999) with the objective of guaranteeing national food security in case of a large reduction in seed stocks and fodder reserves. In case of crisis, it is recommended that the authorities buy large quantities of grain on the international market—mainly wheat for human consumption and barley as fodder—to prevent farmers from selling or consuming the seed for the next crop; this would eliminate local varieties that are well adapted to the climate and unavailable on the international seed market. Assuming that the World food market or stocks are not severely affected by the local drought, this plan seems acceptable.

But severe droughts have occurred in the past, simultaneously affecting several continents and very large areas of the planet. In 1998, following a strong El Niño event, large deficits in grain production were seen simultaneously in China and Indonesia. These two countries were able to import the required amount of grain from the World stocks, and no major adverse consequences were felt. The current global food stocks of cereals, in the order of 400 million tons, which represents about two months of the current global consumption, fell to a very low level but were sufficient. These stocks have been decreasing regularly for the last few years. But a brief look at history may be of interest here. It is well known, for instance, that the Krakatoa volcanic eruption in 1883 had a worldwide effect on temperature and rainfall (a global 5% rainfall reduction is often mentioned); eruptions can thus have a large simultaneous effect on several continents. In 2001, M. Davis published a historical analysis of the nineteenth century famines and described two major drought episodes in 1876–1878 and 1896–1900 that simultaneously affected at least Australia, Brazil, China, India, and Ethiopia. Contrary to the general belief that droughts occur locally and are compensated by surplus elsewhere, severe droughts in this case occurred at the same time on different continents; Davis (2001) relates these droughts to very strong El Niño events affecting the monsoon zones.

The consequences of the 1876–1878 and 1896–1900 famines were very severe; about 30 million people died in China and India alone in each of the two droughts (Davis 2001). Amartya Sen, the 1998 winner of the Nobel Prize in Economic Sciences, also analyzed these events and determined that in most cases of drought, which he called “Food Availability Decline,” the major cause of death and famine was not really the lack of food (Sen and Drèze 1999). Rather, it was the lack of economic resources of the poor farmers whose crops had been lost and who therefore were no longer able to afford the high cost of food. Sen showed, for instance, that drought and agricultural disaster in one part of Ethiopia caused a large famine and many deaths in 1975, even as food and the means of transporting it along a major highway to the famine zone were available in other parts of the country.

In this context, it is of interest to look at the observed historical frequencies of very strong El Niño events. Ortlieb (2000) tried to reconstruct, from historical archives in South America, the years of strong and very strong El Niño events from 1525 to 1950. It can be seen from his list that 1876, 1877, and 1899 were indeed very strong El Niño years, but also that, on average, such very strong El Niño events occur about twice every century.

In conclusion, it seems that once or twice per century, or perhaps more often if climate changes affect El Niño variability, a major drought period, possibly lasting several years, may affect several continents simultaneously, impacting food production at the global scale. Stocks will not be sufficient to satisfy demand, as the current level of stocks will soon be used up, and transporting food to remote places will still be a problem. The international market prices of food will suddenly become very high, and "Food Availability Decline" will occur, generating famines of unknown magnitude. The poor countries or the poor rural communities affected by the droughts will be the first to suffer, but they may not be the only ones. There is no reason to assume that this cannot occur. What is unknown, however, is when it will occur. The only feasible measure to prevent such a catastrophe would be to very significantly increase the World food stocks. A study conducted in India has shown, however, that building up such food stocks is difficult and expensive due to the costs of constructing the storage facility, storing and preserving the food, and preventing losses. It would be preferable if the storage facility costs could be shared between several nations, which also would allow the facilities to be sited where conditions are the most favorable in terms of expense, climatic conditions, transportation networks, means of minimizing losses, etc. Such stocks would also contribute to the stability of food prices, which have become much too "volatile" since 2007, with very severe social consequences. It is also true that during severe food shortages, one could return to a low-energy diet and consume less, but hunger would then be the fate of the less-favored citizens.

7.9 Food Production Efficiency

In agriculture, reducing the water consumption by reducing plant transpiration is not likely to be effective. As shown by Tardieu (2005), genetically reducing transpiration by the leaves is feasible, but this would also reduce carbon dioxide input into the leaves through the same stomata and thus reduce biomass production. There is no known method to reduce one without affecting the other, even with genetically modified organisms. Plants can be made more tolerant to periods of drought: they will survive but not produce. Water can only be saved by reducing the losses between what the plant actually uses and the water brought to the field. These "losses" include evaporation into the atmosphere (water sprinklers and irrigation of bare soils) and infiltration into the ground. But infiltration into the ground is not really a loss; the underlying aquifer is recharged and the water can be used again or will flow into rivers. Furthermore, it is essential, particularly in arid zones, to bring more water than strictly required to leach and drain the soil to eliminate the salts that accumulate in the upper layer due to evapotranspiration. If soils are not drained, soil salinization becomes a major threat to productivity.

The major water savings in agriculture will come about by changes in crops and dietary habits (Table 7.7). The current trend is a strong increase in meat consumption. It is clear from Table 7.7 that a meat diet uses much more water and soil than a vegetarian one. To obtain water savings in agriculture, one must address the human diet issue, together with that of crop efficiency. Human diet also touches on one of the growing major health problems of mankind—obesity—which is due to excessive consumption of high-energy food. Initially limited to a few developed countries,

Table 7.7 Water needed for food production. Average values of water used in cubic meters per ton ($m^3 t^{-1}$) to produce raw food (consumed fraction, not dry matter).

Plant product	Water needed ($m^3 t^{-1}$)	Animal product	Water needed ($m^3 t^{-1}$)
Vegetable oil	5,000	Beef	13,000
Rice	1,500 – 2,000	Poultry	4,100
Wheat	1,000	Eggs	2,700
Corn	700	Milk	800
Citrus fruits	400		
Vegetables	200 – 400		
Potatoes	100		

Source: Académie des Sciences 2006

this problem is now observed in many areas around the World, including developing countries, and requires urgent attention.

Food savings can also be achieved by better care and management. It is reported that 30% of the food bought by consumers in developed countries is actually thrown out, while up to 50% of the crops can be lost to humidity, rats, and other poor storage conditions in many developing countries.

7.10 Water Resources Management in the Twenty-First Century

In normal conditions, the water and soil resources in arid and semiarid zones will not be sufficient to produce the food needed by their populations because of population growth, diet changes, and climate change. Large percentages of virtual water imports—food produced in humid or temperate zones—will be required. Given the growing global food demand, increasing agricultural production should be a major world priority. Although some water savings in agriculture can be expected together with important increases in crop efficiency, it is most likely that food production will require the development of additional rain-fed agriculture. This is particularly true in Africa and South America, where arable land is still available for virtual water trade. Domestic and industrial water supply is, in comparison, a minor problem and can be resolved by water savings or technology. Food saving and diet constraints should be implemented.

Although as yet uncertain, the most likely scenario is that climate change will increase drought frequency, particularly in arid zones. Drought plans should therefore be developed and measures implemented from the beginning of a drought period to organize savings and allocate water to priority users. Food stocks should be increased, particularly in arid zones; in the future, these zones may have to import up to 50% of their food to prepare for periods of worldwide drought.

Societies are much more vulnerable to hydrological changes than to changes that affect only temperature. Therefore, strong research efforts are still needed in climate modeling, extreme events analysis, and paleoclimatology to better constrain the predicted effects of climate change on the water cycle. There is a lack of operational scenarios balancing demand and resources over the next 10–50 years, region by region, as presented for Tunisia, taking into account water withdrawal, water consumption, recycling, and water quality.

Soil conservation should also be a priority, as soil availability will be a major factor for food production. Preventing increases in soil salinity, soil erosion, and loss of organic matter that increases erosion and prevents infiltration is necessary. Creating contour ridges to prevent erosion and increase infiltration should be reconsidered.

But the final goal of twenty-first century water resources management should be to protect and maintain biodiversity. This is probably the most fragile and endangered resource on the planet—far more than water and soil. Research efforts are urgently needed to develop tools to predict the future status and health of ecosystems for any new agricultural, urban, or industrial development. Which compensating measures are required to maintain the ecosystems? Should minimum protected areas be established to preserve nature? When alarming signs are observed, can an endangered ecosystem be restored before it disappears? These are today's unresolved issues, and their solutions require strong cooperation between hydrologists and ecologists.

Note

1. As Asia and North Africa will not be self-sufficient and will have to import food essentially from South America.

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Part II
Learning from History

Chapter 8
The Qanat: A Living History in Iran

Hassan Ahmadi, Aliakbar Nazari Samani, and Arash Malekian

Abstract About 2,500 years ago, Persians invented a number of methods for harnessing groundwater, including a water management system called a qanat. Still used today, qanats are built as a series of underground tunnels and wells that bring groundwater to the surface. They supply about 7.6 billion m^3, or 15% of the country's total water needs, and play a major role in advanced water harvesting. However, many of these systems have been abandoned and replaced by other methods over the past few decades, mainly due to socioeconomic conditions and changing technology. In addition, drilling more deep and shallow wells has hurt groundwater quality—especially in the littoral district of Iran's central plain—which has implications for the environment, people, and economy of Iran. It is necessary therefore to recommend and implement relevant solutions to increase the efficiency of qanats to achieve sustainable development in water resources management.

Keywords Arid region · Groundwater management · Iran · Qanat · Water gallery

8.1 Ab: High Demand in a Land of Scarcity

The word for water in Persian, ab (pronounced as äb), consists of two letters: A and B. Water is the alphabet of life, survival, and reclamation. Water, fire, and soil were valued as holy aspects of nature in ancient Persia. Water, however, has not always been easy to come by in arid and semiarid regions of the country, where rainfall events are very rare. Annual precipitation in Iran is 273 mm—less than one-third of the world's mean annual precipitation (Mahdavi 2004; Alizadeh 2005). The temporal and spatial distribution of rainfall is not uniform; about 75% of the nation's precipitation falls in a small area, mostly in the southern coast of the Caspian Sea, while the rest of the country receives insufficient precipitation. On a temporal scale, 25% of the precipitation falls during plant growth season (Jamab 1998;

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DOI 10.1007/978-90-481-2776-4_8,

Mahdavi 2004). High density, short-duration rainfall often generates destructive floods. Similar conditions prevail in many other countries in the region.

While rainfall is low relative to the world's mean annual precipitation totals, the demand for drinking water has been increasing in the last three decades due to rapid population growth. Annual per capita renewable water in Iran totals 1,500 m^3 (one-fifth of the global average) (Papoli Yazdi 2000; Alizadeh 2005; Saffari 2005).

The need for people to overcome the challenges of an arid climate to meet water demand is nothing new. Approximately 2,500 years ago, Persians invented a number of methods for exploiting, conserving, and storing surface water and groundwater. One of these techniques for water management is called a qanat, a technological and advanced system for water exploitation that has demonstrated through the centuries the ability of humans in arid regions to transform a harsh environment into a habitable area. The qanat is essentially a horizontal, interconnected series of underground tunnels that collect and deliver groundwater from a mountainous source area, along a water-bearing formation (aquifer), and to a settlement (Perrier and Salkini 1991). The tunnels, typically several kilometers long, are roughly horizontal, with a slope. Driven by gravity, water drains to the surface to lower and flatter agricultural land.

Considered to be the oldest feat of human engineering, this system is still used in a limited number of places in Iran, North Africa, China, the Arabian Peninsula, Afghanistan, and beyond. The system is referred to by different names in different regions: qanat and kareez (Iran); kariz (Afghanistan and Pakistan); kanerjing (China); khettara (Morocco); galeria (Spain); aflaj (Oman); and kahn (Baloch) (Goblot 1979; Al-Rawas and Hago 1999; Pouraghniaei and Malekian 2001). In North Africa, the qanat is called a foggara (Al-Rawas and Hago 1999; Lightfoot 2003; Sankaran Nair 2004). However, the qanat system may not be applicable for solving the present-day challenges of water resources scarcity in arid and semiarid regions of the world.

8.2 The Qanat System: A History

In the early part of the first millennium B.C., Persians started constructing elaborate tunnel systems for extracting groundwater in the dry mountain basins of what is now Iran because surface water resources were insufficient for domestic and agricultural purposes (English 1968; Beekman et al. 1999).

From 550 to 331 BC, when Achaemenid Persian rule extended from the Indus to the Nile, qanat technology spread throughout the empire. An earthquake in December 2003 uncovered an old city and a qanat system in Bam, Iran, that dated back more than 2,000 years. Preliminary studies indicate that this qanat was built in the time of the Seleucids-Achaemenids (312–60 BC).

The Achaemenid rulers provided a major incentive for qanat builders and their heirs by allowing them to retain profits from newly constructed qanats for five generations. As a result, thousands of new settlements were established and others expanded. To the west, qanats were constructed from Mesopotamia to the shores of the Mediterranean, as well as southward into parts of Egypt (Pearse 1973; Goblot

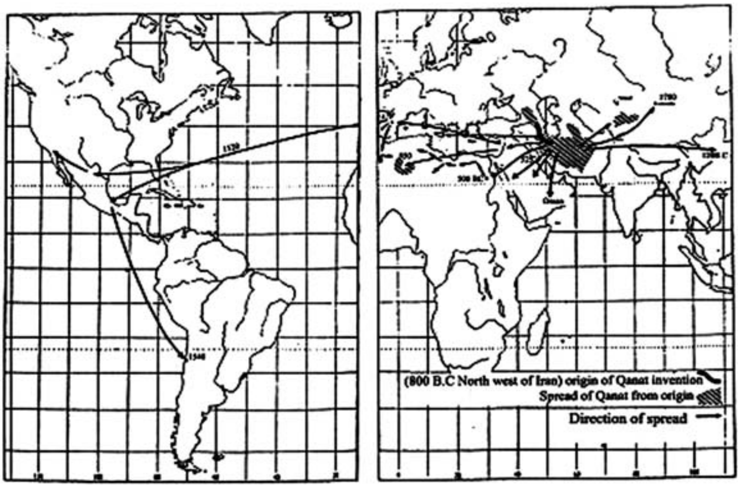

Fig. 8.1 Qanat origin and distribution. (Source: Papoli Yazdi 2000)

1979; Pazwash 1983). To the east of Persia, qanats were constructed in Afghanistan, the Silk Road settlements of Central Asia, and Chinese Turkistan (see Chapters 9 and 10). The expansion of Islam prompted another major diffusion of qanat technology. The early Arab invasions spread qanats westward across North Africa and into Cyprus, Sicily (Italy), and Spain, including the Canary Islands (Fig. 8.1). In Spain, Arabs constructed one system at Crevillente, most likely for agricultural use, and others in Madrid and Cordoba for urban water supply. Evidence of qanats in Latin America can be found in western Mexico, Peru, and Chile (Goblot 1979; Papoli Yazdi 2000). Without this innovation, ancient civilizations would not have been able to survive in arid and semiarid regions, which cover 20 million km^2 of the world (Nazari Samani and Farzadmehr 2006; Papoli Yazdi 2000; Saffari 2005).

In modern times, however, social, technological, and economic changes generally have led to the widespread abandonment of the traditional use of qanats; with their decline, a large proportion of the traditional knowledge and social organization surrounding the systems also is vanishing.

8.3 Construction: Locating a Site and Digging the Tunnel

Physically, qanats are environmentally sustainable systems of groundwater extraction. In the plateau regions of Iran, water obtained from the subsurface in this way is used for domestic and agricultural purposes. As a man-made tunnel, the qanat has enabled settlers to find new pastures in the desert. The first settlers who lived in the natural oases might have developed the idea of a qanat to bring arid but fertile terrain under cultivation and make the land habitable (English 1968; Hajie 1997; Papoli Yazdi 2000).

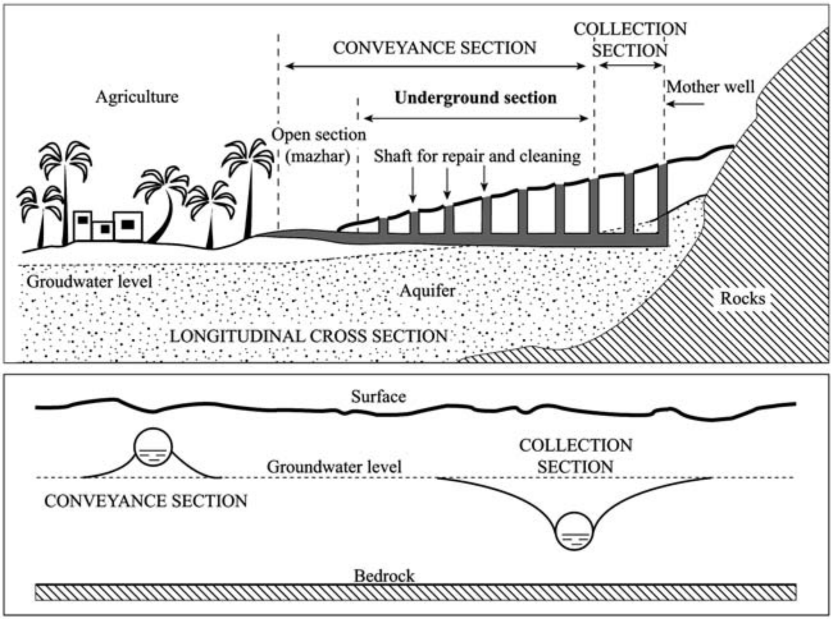

Fig. 8.2 Qanat construction and its sections. (Source: Nazari Samani and Farzadmehr 2006)

The first step in building a qanat is locating a suitable aquifer. Builders must have special skills and excellent knowledge of the topography and geomorphology of the area. A qanat consists of three parts: a mother well, an underground tunnel, and shafts, or milleh (Fig. 8.2). The mother well sits at the beginning of the qanat and is dug at the upslope where the groundwater table is close to the surface. The cross section of the tunnel is usually elliptical, with a height of about 1.2 m and a width of about 0.8 m. To provide ventilation for the workers in the tunnel and to facilitate the removal of debris, a series of vertical shafts are dug about 20 m apart along the line of the tunnel (Afkhami 1997; English 1968; Nazari Samani and Farzadmehr 2006; Papoli Yazdi 2000). The depth of the shaft from ground level increases toward the mother well. The tunnel, or gallery, has a slope gradient of 0.3–0.5% to maintain a balance between excessive erosion and sedimentation of the tunnel bed. Water flows from its source at the mother well, along the gently sloping tunnel, to the qanat outlet, called a mazhar (Al-Rawas and Hago 1999; Nazari Samani and Farzadmehr 2006). The mazhar is similar to a mine entrance, and the water that flows out from a qanat is naturally “mineral” water (Siahpoosh 1973).

The major part of the tunnel is constructed above the water table; when it hits the water table, upslope construction continues below it until the mother well is reached. Based on hydrologic processes, qanats are divided into two sections (see Fig. 8.2). The first section is collection, in which water infiltrates the tunnel from the aquifer. The groundwater table is above the tunnel in the collection section. In the second section, conveyance, water flows through the tunnel. Therefore, the tunnel forms a relatively short "wet" section, which is in fact an underground drain into which groundwater seeps. This is the water-producing section of the qanat. The downslope section is the "dry" section, which merely acts as the transportation segment. Whereas the wet section is only a few tens of meters long, the dry section may extend over several kilometers. To decrease water infiltration, the tunnel beds are covered by an impermeable material such as sarooj (an ancient Persian name for a kind of concrete produced by a mixture of clay, lime, wood ash, reed, water, and egg used in hydraulic structures) and compacted clay (Pouraghniaei and Malekian 2001; Saffari 2005).

The depth of the mother well varies but typically is about 10–250 m. According to historical findings, mother wells of 450 m have been discovered from Achaemenid times in Iran. Stretching about 270 m, the deepest active mother well in arid regions of the country is in Gonabad in the Khorasan province of eastern Iran (Papoli Yazdi 2000). The tunnel length of a qanat varies between a few hundred meters up to 120 km. A qanat in Yazd, for example, boasts a total length of 120 km, with a mother well that is 116 m long (Davarpanah 2005; Saffari 2005). The average length of a qanat is 25 km in eastern and northeastern parts of Iran where piedmonts are large and water scarcity is a dominant characteristic; in other parts of the country, the length of a qanat averages about 6 km.

Qanats are constructed by specialists who work in a team headed by a muqanni. The muqanni excavates the tunnel with a small pick and shovel, while his apprentice packs the loose dirt into a leather bucket. Two laborers at the surface of the shaft remove the dirt using a hoist (Fig. 8.3) (Hajie 1997). This windlass is known as a charkh in Persian and as the spinning wheel in some other parts of the world. Teams

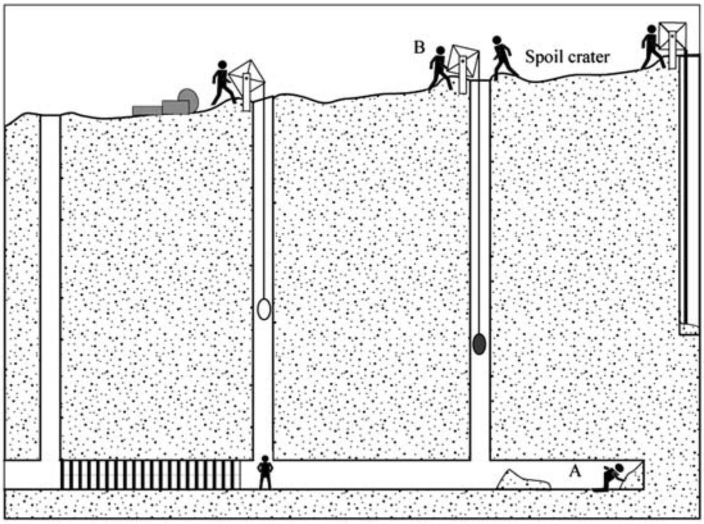

Fig. 8.3 Constructing a qanat, **A**: muqanni, **B**: laborers. (Source: http://www.waterhistory.org)

Fig. 8.4 Constructing qanats using reinforcing rings. Note the spoil crater from digging the well. (Source: Ghayour 2000)

can remove 3,000–4,000 tons of rock from a tunnel measuring 1 km long and 1.5 m in diameter. A windlass is set up at the surface and the excavated soil is hauled up in buckets (Sankaran Nair 2004).

The spoil is dumped around the opening of the shaft to form a small mound; the mound keeps surface runoff, silt, and other contamination from entering the shaft (Hosseini 1997). A vertical shaft measuring 1 m in diameter is thus dug out. The team then constructs a gently sloping tunnel that transports water from groundwater wells to the surface some distance away. If the soil is firm, no lining is required for the tunnel. In loose soil, reinforcing rings are installed at intervals in the tunnel to prevent cave-ins (Fig. 8.4). These rings are usually made of baked clay called nays (Hosseini 1993).

Mineral, salt, and other deposits that accumulate in the tunnel bed necessitate periodic cleaning and maintenance (Siahpoosh 1973). The muqannis undertake digging, cleaning, and repairs—hazardous work for which they are paid handsomely. Floods and soil spill into the qanat tunnels frequently, and deaths among muqannis occur. The muqannis command respect and have inspired a body of folk customs and beliefs. A muqanni will not work on a day he considers to be unlucky or if he sneezes that day (Papoli Yazdi 2000). Older muqannis are considered blessed and prayers are performed each time they descend into a qanat (Hosseini 1993; Afkhami 1997).

Before taking up the actual construction of the qanat, the muqanni decides the site of the mother well (madar chah). This forms the origin of the qanat and lies at the extreme end of the settlement. After deciding the potential site for the madar chah, the muqanni digs one or more trial shafts (gamaneh). The location of the mother shaft depends on a number of factors: local slope conditions, the surrounding landscape, subtle changes in vegetation, available groundwater, and the anticipated destination of the water.

After the builders dig the mother well, they move downslope and decide the destination point, through the collection gallery, where water surfaces. The excavation of the tunnel starts from there, burrowing back almost horizontally toward the mother well. Crouching, the builders hollow out the tunnel with a hammer and chisel and dig the vertical shafts. In some cases, the builders dig these shafts first and then chisel out the tunnel to connect their bases. The successive vertical shafts look like a line of ant-hills, stretching for miles. When viewed from the air, they indicate the course of the qanat from the source to the outlet. The holes are left open after the underground canal is completed, enabling subsequent inspection and repair (Goblot 1979).

Once a trial shaft has struck water, and the shaft becomes the mother well of the qanat, the length of the tunnel can be determined by measuring the distance between the mother well and where water surfaces. Land subsidence can occur if the qanat is misaligned and emerges some distance away from the settlement (Nazari Samani and Farzadmehr 2006).

To achieve the maximum yield from qanats, the systems must be kept in good condition. In the past, qanats were maintained through teamwork, with participation from all those benefitting from the water or from people hired by them. This is a large task, and difficulties in ensuring maintenance have caused silt to build up in many qanats, rendering them inefficient. These difficulties arise essentially from the time required for repairs and high maintenance costs. In Yazd province, for example, saving one liter per second of a qanat's yield costs $1,187.50 (US), which the owners cannot afford (Najib and Mohammadi 2002; Safi Nejad 2000).

In many villages, qanat ownership is widely diffused throughout the population, and this widespread stake in the water supply system reinforces social cooperation. Qanats are usually initially built by wealthy individuals, but the constant need for tunnel repair, due to natural disasters or social dislocations, leads to rapid fragmentation of their ownership. Many qanats have up to 200–300 owners, and the water may be divided into as many as 10,000 time shares. In some cases, the system of dividing water dates back hundreds of years. The current division of water at Ardestan in central Iran, for example, dates back to the 1200s, when Hulaku Khan, the grandson of Genghis Khan, ordered that the town's water be divided into 21 shares with each share allotted to a specific quarter (Najib and Mohammadi 2002). In this case, every owner has a small share of the water and little vested interest in paying the maintenance costs. A politically strong power is usually needed to organize the work (Davarpanah 2005; Jamab 1998).

8.4 Continuous, Parallel, Convergent, and Two-Layered Qanats

Based on location, qanats are divided into two groups: mountainous and plateau. The main differences between the two groups are geological formation conditions, the length and feeding area of the qanat, the depth of the mother well, discharge, and physiographic conditions. The length of qanats and depth of the mother well in mountainous regions are smaller than those on plateaus, and the qanats

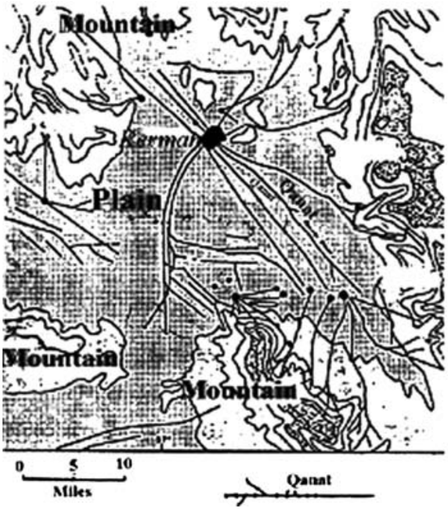

Fig. 8.5 Convergent qanat in Kerman (southeast Iran). (Source: Ghayour 2000)

generally have a seasonal discharge. Mountainous qanats are constructed on alluvial depositions at the bed of a stream and dry rivers in outlets of a watershed, while the plateau qanats are located in the dry plains of Iran. Qanats can also be divided into continuous, parallel, convergent, and two-layered classes according to shape, geomorphologic conditions, and topography (Papoli Yazdi 2000; Pouraghniaei and Malekian 2001).

Continuous qanats are found in mountainous valleys with high gradient slopes. With this type, some qanat branches are positioned consecutively so that excess water of each qanat feeds the next qanat, usually after irrigating farm lands. Parallel qanats are located in a pediment plain with the mother well close to a mountain. Convergent qanats are located in a plain surrounded by mountains. In this configuration, numerous qanats radiate to a central plain (Fig. 8.5) (Ghayour 2000; Nazari Samani and Farzadmehr 2006).

Two-layered qanats are rare, complex, and short structures (Fig. 8.6). The most striking example of this type of qanat is in Zavareh in central Iran. It is 2 km long and has 30 shafts. Each layer has a different mother well and tunnel. In these qanats, the upper tunnel cuts the shafts in a semi-radial direction. These qanats are constructed where two aquifers are separated by impermeable layers; consequently, two qanats are independently fed by different aquifers (Papoli Yazdi 2000).

8.5 Using Qanats for Cooling

In addition to water management, qanats can serve as cooling systems. In dry and desert lands, the average temperature of the summer season (June–September) is about 30°C. The arid regions of Iran have fairly fixed seasonal and daily wind patterns. A wind tower harnesses the prevailing summer winds to cool the inside of a

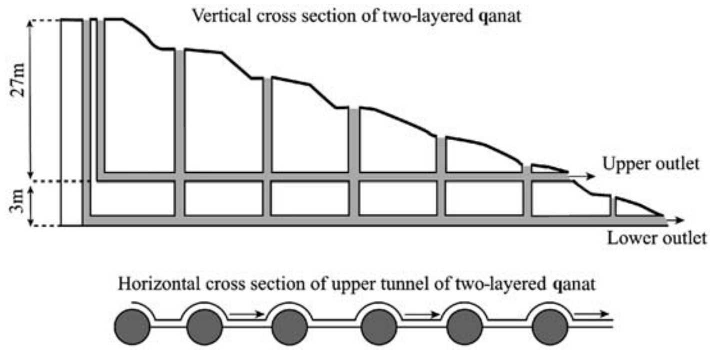

Fig. 8.6 Horizontal view and cross section of a two-layered qanat in central Iran. (Source: Ghayour 2000)

building. A typical wind tower resembles a chimney, with one end in the basement of the building and the other end rising from the roof. Wind tower technologies date back more than 1,000 years (Bahadori 1978).

The passive cooling of a wind tower can be enhanced by connecting it to a qanat. In the system shown in Fig. 8.7, a shaft (b) connects the qanat to the basement of the building. Hot, dry air enters the qanat through one of its vertical shafts (a) and is cooled as it flows along the water. Because the underground water is usually cold, the rate of cooling is quite high. The wind tower is placed so that wind flowing through the basement door of the tower passes over the top of the qanat tunnel. When the air flows from the tunnel through the door, its pressure decreases. The

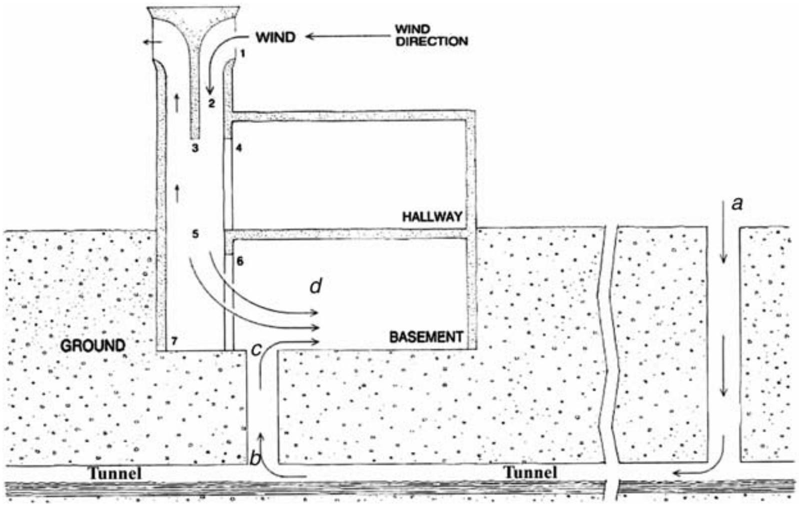

Fig. 8.7 The airflow in a combination wind tower/qanat cooling system. (Source: Bahadori 1978)

pressure of the air from the tower is diminished further when it passes over the top of the tunnel so that cold, moist air from the shaft combines with the flow of cooled air from the tower (c). The mixture of air from the qanat and air from the tower (d) circulates through the basement. A single qanat can serve several wind tower systems (Bahadori 1978; Saffari 2005).

8.6 Benefits and Disadvantages of Qanats

Qanats offer a number of other benefits aside from their role in water harvesting and cooling. For example, in the Khorasan province in east and northeastern Iran, 7,387 qanats were used in 1980 for a total discharge of 77.8 m^3/sec. As a comparison, a concrete arch dam that stands 60 m tall in Kardeh, a city in Khorasan province, has a discharge of 1 m^3/sec (Siahpoosh 1973; Davarpanah 2005; Saffari 2005). In addition, 12,072 deep and shallow wells with an annual discharge of 5.6 billion m^3/yr were exploited in Khorasan (4.6 million m^3 per well).

Compared to wells, the qanat as a water delivery system has a number of advantages: (1) it reduces water loss from evaporation because the majority of the tunnel is underground; (2) it does not require pumps because the system relies entirely upon gravity; (3) water harvested by the system costs less; (4) it draws on indigenous knowledge and local expertise; (5) it drains saline and alkaline soils and aquifers; and (6) it exploits groundwater as a renewable resource (Davarpanah 2005; Nazari Samani and Farzadmehr 2006).

The last benefit warrants additional discussion. The rate of water flow in a qanat is controlled by the level of the groundwater table. Thus, a qanat cannot cause significant drawdown in an aquifer because its flow varies directly with the subsurface water supply. When properly maintained, a qanat is a sustainable system that provides water indefinitely. The self-limiting feature of a qanat, however, is also its biggest drawback when compared to the range of technologies available today, including deep wells. Water flows continuously in a qanat, and although some winter water is used for domestic use, much larger amounts of irrigation water are needed during the daylight hours of the spring and summer growing seasons (Fig. 8.8).

Although this continuous flow is frequently viewed as wasteful, it can, in fact, be controlled. During periods of low water use in fall and winter, water-tight gates can

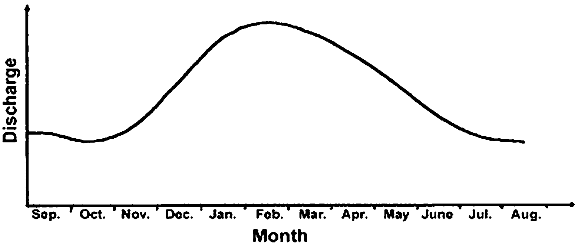

Fig. 8.8 Annual discharge variation of a qanat. (Source: Davarpanah 2005)

seal off the qanat opening, damming up and conserving groundwater for periods of high demand. In spring and summer, night flow can be stored in small reservoirs at the mouth of the qanat and held there for daytime use.

A qanat system has several disadvantages, however, besides the potential loss of wintertime flow (Najib and Mohammadi 2002; Pouraghniaei and Malekian 2001): (1) unlike wells, the system is unable to use an aquifer's entire thick layer; (2) maintenance and cleaning can be difficult, costly, and time consuming; (3) it requires a suitable topographic, lithologic, and hydraulic gradient of the aquifer; and (4) the probability exists of groundwater pollution through its shafts.

In addition, qanats frequently have been used for domestic purposes, making them potential transporters of disease (WaterHistory.org). A 1924 chemical analysis of water from six qanats where they entered Tehran revealed water suitable for drinking in only two cases. In three others, potability was questionable, and in one case the water was unsuitable for drinking. It has been hypothesized that qanats were a major contributor to cholera epidemics of the nineteenth century. Throughout Iran, even if the qanat water was uninfected before entering the cities, water had ample opportunity to become contaminated while traversing urban areas in open ditches. With the lack of proper sewage and waste disposal throughout Iranian municipalities, the cholera bacterium easily made its way into drinking water (Davarpanah 2005; Hosseini 1993; Saffari 2005 see Chapters 5, 6, and 13).

8.7 The Decline of Qanats

Considering that the average length of each qanat is 6 km in most parts of the country, the total length of 30,000 qanat systems is about 310,800 km—about 7.7 times the Earth's circumference. This shows the enormous labor and energy used in qanat construction. In fact, more than 38,000 qanats were active in Iran until 1966, but that number had fallen to 20,000 by 1998 and is currently estimated at 18,000 (English 1968; Pouraghniaei and Malekian 2001; Ghayour 2000).[1] Moreover, while 30–50% of Iran's total water needs were supplied through qanats in 1965, that number has fallen to 15% in recent decades.

Although the benefits of qanats are well known, the system has declined for two main reasons: technical problems and socioeconomic issues. The increase in water use for agricultural irrigation expansion, the drawdown of the groundwater level, floods, difficulties in maintenance, and sediment problems are among the technological factors. Social and economic factors include the decrease in agricultural income, the collective ownership of qanats, the managerial focus on wells instead of qanats, and a change in the social structure of the rural communities in Iran.

The most important cause of the decline is an increase in the number of deep and semi-deep wells. Sparked by a spike in population growth and water demand, drilling these wells caused the drawdown of the groundwater level. As the population grew, people drilled more and more wells to cover the deficit, igniting a vicious

Table 8.1 Groundwater discharges from aquifers in Iran

Year	Number of wells	Discharge (Billion m^3)
1994	374,634	57.65
1995	407,398	59.41
1996	424,010	60.95

Table 8.2 Cost of 1 m^3 of water per second from wells and qanats in Iran in thousands of rials, the Iranian currency, and (US dollars)

Interest rate (%)	Diesel Well	Electrical Well	Qanat
10	89.6 (112.0)	67.5 (84.4)	41.2 (51.5)
15	103.7 (129.6)	88.8 (111.0)	56.3 (70.4)
20	118.9 (148.6)	111.4 (139.3)	71.5 (89.4)

cycle of drilling and drawdowns that has affected the discharge of qanats in recent years (Najib and Mohammadi 2002).

In addition, changes in cropping patterns designed to obtain higher returns meant more water was needed than qanats could provide. Moreover, the lands located at elevations above the mouths of qanats could not be irrigated by the qanats themselves. Wells provided a solution to these problems but caused a decrease in the amount of water the qanats yielded. Compared to wells, qanats are very sensitive to water level fluctuations, and the flow of water in qanats varies from year to year depending on the recharge rate of the aquifer (Table 8.1). In the Middle East, where drought hits on average once every four years, this uncertainty often results in conservative cropping strategies geared to the cultivation of low-risk, low water-consuming, low-value crops like wheat and barley (Nazari Samani and Farzadmehr 2006).

As a result of the development of well technology in Iran in recent years, farmers are increasingly relying more on wells than on traditional techniques. Wells are more expensive to build than qanats, but they provide larger quantities of water and cost less to maintain (Table 8.2) (Jamab 1998; Najib and Mohammadi 2002).

8.8 Sustaining Qanats for Sustainable Development

Developed in antiquity, qanats are traditional systems of harnessing groundwater to meet water demands. Enduring for centuries, qanats are now in decline due to socioeconomic forces and changing technology. Advantages of the qanat system include its simple structure, its harmony with the environment, and its ability to tap groundwater in arid areas. It has drawbacks, however, including water loss during seasons of low demand and maintenance costs.

Action is necessary to save and preserve these precious assets. Steps toward preserving the ancient system include flood control, organizing groundwater utilization through wells, using surface water resources for the artificial recharge of aquifers, decreasing water loss, and repairing and preserving old qanats.

A qanat system has a profound influence on the lives of the water users. It allows those living in a desert environment adjacent to a mountain watershed to create a large oasis in an otherwise stark environment. The United Nations and other organizations have recognized the value of the qanat for sustainable water use and are encouraging the revitalization of traditional water harvesting.

Note

1. The number of qanats cited may vary by author depending on sources used.

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Chapter 9
Notes from the Turpan Basin: Pioneering Research on the Karez

Iwao Kobori

Abstract The karez in China is a unique example of the underground tunnel irrigation systems that were developed by the Persians in ancient times and spread to many regions of the globe. Until relatively recently, it had been difficult for foreign researchers to study the karez in the field because of limited access to the interior of Asia. But in 1981, a Sino-Japanese mission was organized to explore the karez system in the Turpan Basin in China's Xinjiang province. The author, Iwao Kobori, professor of drylands and desertification at the United Nations University in Japan, was part of that mission and has spent decades studying and documenting the karez system. Today, while the use of the karez is, generally speaking, declining, the research conducted by the mission, as outlined in the chapter, is valuable for conservation and restoration.

Keywords Karez · Qanat · Turpan · Uygur · Xinjiang

9.1 Origin and Diffusion of the Karez

In April 1981, with the collaboration of Chinese scientists and engineers in Xinjiang, I was able to examine the karez system in Turpan and summarize the status of the system there based on research in situ and data collected locally[1] (Fig. 9.1).

The history of the karez (in the Uygur language) in China's Xinjiang province has been an important key for understanding the origin and diffusion of the qanat irrigation system of Persia in antiquity (see Chapter 8). Historical records in ancient China, such as the following by Suma Chien, who chronicled events about 2,000 years ago, offer some clues about the water management system's past (Needham, 1954):

> After that (i.e., c. 120 BC) . . . the people of Lin-chin wanted to open a canal which would leave the river Lo and irrigate 10,000 *chhing* of land lying east of Chung-chhüan. This land

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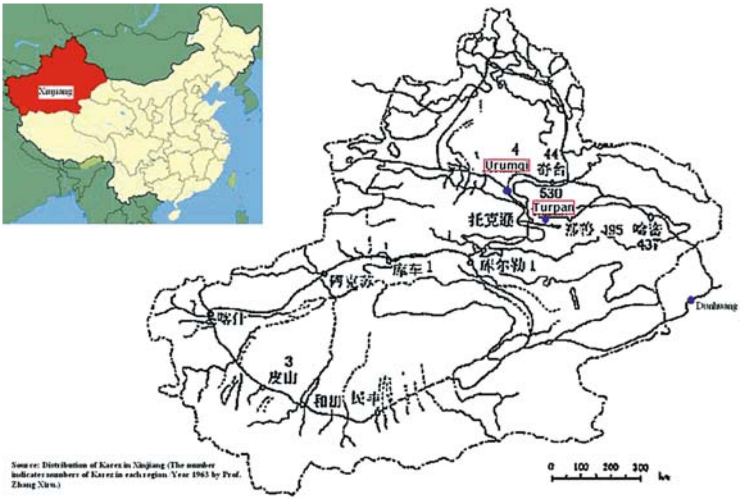
G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
DOI 10.1007/978-90-481-2776-4_9,



Source: Distribution of Karez in Xinjiang (The number indicates numbers of Karez in each region Year 1963 by Prof. Zhang Xiru.)

Fig. 9.1 Distribution of karezes in Xinjiang (The number in the map indicates the number of karezes in each region). (Source: Submited by Prof. Zhang Xiru. For details, see Note 3)

> had previously been salty, but if one could really succeed in getting water for it, a harvest of ten *tan* for every *mou* could be obtained. Accordingly, more than ten thousand laborers were recruited for the work, and they cut a canal from the city of Cheng, which brought the waters of the Lo to the foot of Shang-yen Mountain. As the banks were liable to slide and crumble easily, a series of wells was dug, the deepest of which was 400 feet, and there were wells all along at regular intervals. At the bottom they communicated with each other by a tunnel through which the water flowed. The water flowed around the Shang-yen Mountain, the canal continuing east more than ten *li* until it reached the hills. This was the first time that a subterranean canal with well-openings (Ching Chhü) had been built.

The Chinese historian Wang-kuo-wei cited the above quotation, and assumed that this technique of ching chhü was introduced to western China. However, the existence of the qanat/karez in Persia had already been mentioned by Polibius before Wu-ti (180–87 BC) of the Han Dynasty. The first Chinese to mention qanats in Persia could be Chang Te in his *Hsi Shih Chi* (*Notes on an Embassy to the West*) in 1259 AD, in which he described qanats around the Elburz Mountains.

As we do not have sufficient current information on the topography of the project mentioned by the ancient historian Suma Chien, it is fairly difficult to discuss the similarity between Chinese and Persian techniques, and further comparative studies are needed. But how and in what way were the influences and transmission of qanat/karez technology across Central Asia possible? Scholars such as Needham (1954) have posited that the influence probably traveled from west to east, if Laessøe (1951) was correct in recognizing the existence of qanats in the eighth century BC in the Urartu Kingdom (now Armenia). Needham's hypothesis is well accepted among qanat/karez researchers, and Goblot's book, *Les Qanats* (1979), is still well read.

Another mention in China appeared at a much later date. Lu Jung in his *Shu Yuan Tsa Chi* (1475 AD) wrote:

> In the capital of Shensi there had formerly been very little water within the city, and the wells were so few that the inhabitants generally fetched their water from outside the west gate. When Yü Tzu-Chün became governor of Sian, he reflected that Kuanchung (the Wei Valley) was a strategic region, and that if the city were besieged for several days, the inhabitants would hardly be able to live. So he bored an underground canal leading the waters of the rivers Pa and Chhan into the city from the east, and letting [sic] them flow out to the west. The water was obtained by means of a series of shafts with a masonry lining (*huan chou),* the water flowing in the tunnel below and the ground being quite level above.

But the karez never became widespread in inland China, probably because the physiographic and geologic environment was not suitable for constructing the system.

A better understanding of the Karez in China requires further analysis of its present status and the collection of oral history regarding the development of the system as well as a comparison of the structure, technique, and other elements of the karez in other countries.

9.1.1 The Karez in Turpan

In the Turpan Basin, in eastern Xinjiang, the karez is called kan-ch'ing or kanerjing in Chinese.[2] The first Chinese document referring to a karez (kanerjing) in the Turpan Basin was written by Lin Thü Shü when he visited the water works in southern Xinjiang in 1845 AD. His diary states, "There are many earthen holes which are called Kan-ching by local peoples. The water flows horizontally in the tunnel." According to his note, it is assumed that karez systems were relatively numerous in the Turpan Basin either in the late Ming or early Qing dynasties, which ruled from 1368 to 1644 and from 1644 to 1912, respectively.

The political centers of Turpan before the Ming Dynasty were Chiao Ho, Kao Chang, and Lukusun. The water supply to those areas depended on springs or wells, and there is no trace of the karez system up to that time. For instance, Chiao Ho, which was built in the Si Han Dynasty (around the second century BC), has a stream and several wells.

9.1.2 The Story of Arupu

In 1961, C.Y. Han, a hydraulic engineer for the Bureau of Electricity and Water of Turpan County, conducted what turned out to be a very valuable interview with an 80-year-old man named Arupu.

Arupu was born into a kun chang family (karez specialists), which existed for more than five generations. In 1871, when new castles were built in Turpan, numerous karezes provided water for the inhabitants and livestock and irrigated agricultural lands. At that time, the majority of kun chang were Chinese. The Suleiman

Mosque was built between 1770 and 1777, and we found traces of old karezes around it. From this information and Han's interview, we understood that Arupu thought that karezes had existed in Turpan for 300 or 400 years. Furthermore, most of the old karezes are known by Chinese names. The unit for the measurement of the length of a karez is ho. Ho equals the distance between two outstretched arms, or approximately 1.5 m. The output of the tunnel is called shui ho. Tools for the construction of a karez also were given Chinese names, such as uru, which is a grinder pulled by a bull. With these various sources, Arupu believed that the origin of the karez was Chinese.

I do not agree with Arupu on this point. For instance, the measurement unit called ho in Chinese exists in Iran, where it is called farsang. Such terms may have been given after Chinese immigrants settled in Turpan and became owners of the land.

On the other hand, American geographer E. Huntington quoted Arupu's interview in *A Beg and a Mullah of Lukchun* (1903): The "karez was introduced from Persia or the Transcaspian region around 1780 when the kings of Suleiman constructed minarets at Turpan." This introduction was seconded by A. Stein, who surveyed archaeological sites of Xinjiang in the 1930s, and others who support the origin and diffusion of the karez system from the west through Central Asia. These two contradicting discussions could not be definitely resolved by documents alone.

9.2 Characteristics of a Karez

The physiographic environment and geological conditions of the Turpan Basin offer the right conditions for digging a karez (Fig. 9.2).[3] Hydrogeological conditions of the basin include several abundant water sources. Mt. Bogdo-ola in the north and Mt. Kulaucheng in the west have plentiful rainfall and many glaciers. Snow melts every summer and autumn and rainwater flows into the basin. At the piedmont of those mountains, water percolates through the rough gobi (gravel) that covers the land. River water flowing from the mountains penetrates under the ground to form large water reservoirs.

The highest summit of Bogdo-ola is 5,445 m, and the water level of Aitin Lake in the center of the basin is –155 m. The horizontal distance between the Tian Shan range and Aitin Lake is about 60 km and the vertical difference is about 1,400 m. The average slope of the ground surface is approximately 1/40 and the groundwater is not too far below the surface. A karez is usually 3–4 km in length and requires approximately 10,000 m^3 of earth and stones. Geologically, the deep strata of gobi, sand, and clay are solid enough to build the underground system. To the south of the Ho Yen Shan range, pebbles with clay offer the same conditions. Only in those parts where sand, gravel, and pebbles are loosely concentrated is careful maintenance needed and carried out regularly.

The Turpan Basin has a typical continental desert climate. Average annual rainfall is less than 13 mm and the annual evapotranspiration exceeds 3,600 mm. The absolute maximum temperature is 49°C. Temperatures exceed 40°C more than

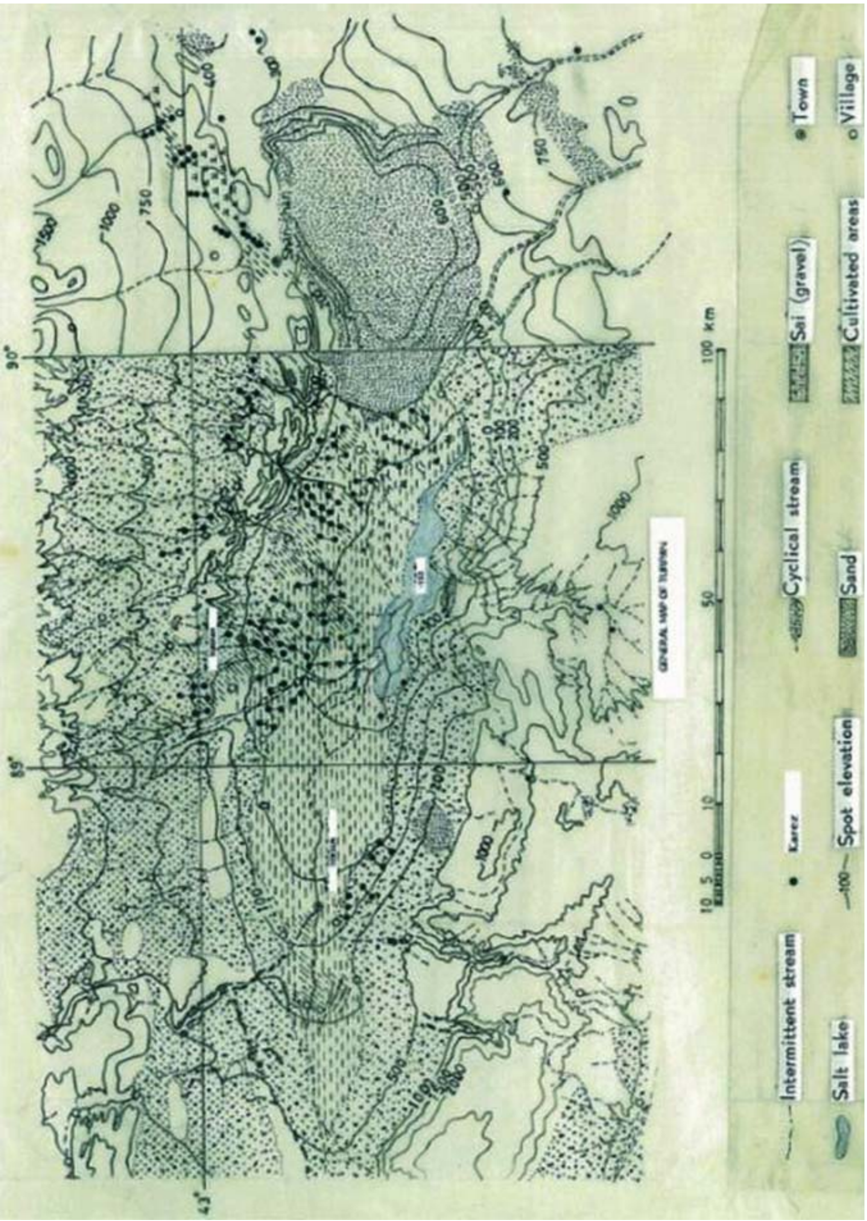


Fig. 9.2 General map of Turpan (1963)

Fig. 9.3 Typical water pond (raobai) in Turpan. (Source: the author)

30 days each year; strong winds blow more than 20 days annually. Under these severe conditions, however, a karez guarantees water for domestic use and irrigation; even a heavy sandstorm cannot bury the water systems.

A karez is divided into several parts. The first is called chien ch'ing or riu ch'ing (shaft well) or kung tso ch'ing (operation well). This is a vertical well used for digging, repairs, and ventilation. Accumulations of soil dug from the shaft wall and underground tunnel are piled around the entrance of a chien ch'ing. The second part is called raobai, which is a kind of reservoir, or water pond, for irrigation water (Fig. 9.3). The raobai holds water in quantities of approximately 30 to several hundred cubic meters. An irrigation officer controls the distribution of reserved water on a 24-hour basis.

The distance between shaft wells varies from point to point (Fig. 9.4). The cross section of the shaft well is oval and generally measures 1.0 by 0.7 m. Usually a karez of about 3 km has approximately 120 shaft wells. Tree branches, kaoliang (a type of grain sorghum), and gravel at the entrance of each shaft prevent freezing in

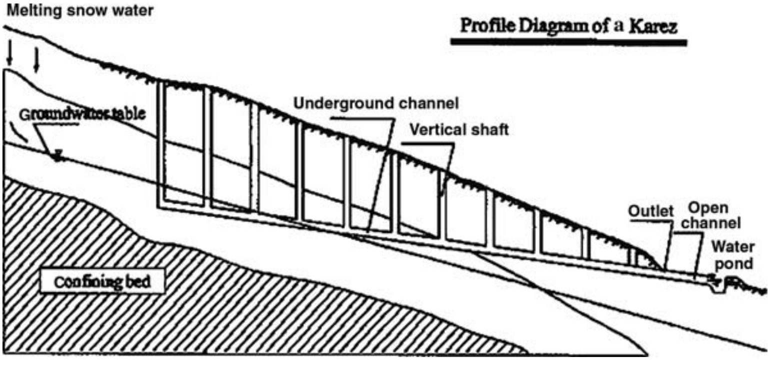


Fig. 9.4 Cross section of a karez. (Source: Karez in Xinjiang 2005)

Fig. 9.5 Cleaning an underground tunnel of a karez in Turpan. (Source: the author)

winter and damage caused by melting water in spring. The entrance is opened in the summer but usually is kept closed to prevent sand sedimentation by strong winds.

Anchii, an underground tunnel or channel, takes the groundwater to the surface. Generally speaking, the upstream segment (called the shui ho in Uygur), where the water flows out, is 200–300 m long and usually occupies approximately one-tenth of the total length. The downstream segment, the kan ho, stretches a few kilometers. The average slope of the tunnel is about 1/500, and the water depth is 0.3–0.5 m. The seepage of water to the ground in the kan ho section is fairly large, and 10.5% of the water is lost each kilometer, according to an estimate by Han, the hydraulic engineer who interviewed Arupu. Because of the continuous water flow, the cross section of the anchii is constantly increasing in size.

The life of a karez is about 10 years.[4] When it is broken and no further maintenance is possible, another is built nearby. This method is surprisingly similar to that of qanats in Iran or the foggara systems in the Sahara (see Chapters 5 and 6). Generally speaking, the maintenance of a karez includes the collection of accumulated mud or sediment every one or two years, a task that requires 200–300 workers (Figs. 9.5 and 9.6).

Fig. 9.6 Inside a typical karez in Turpan. (Source: the author)

9.3 Irrigation

Karez systems have been the main water source for domestic and agricultural use in the Turpan Basin. Gravity continuously moves the water through tunnels, and water is not lost through evaporation, as surface water is. The groundwater extracted through a karez has moderate discharge and few mineral components, and such water irrigates the oasis to produce cotton, grapes, and Hami melons. In 1980, 829 karez systems existed in the area, with a total length of about 2,360 km and a discharge of 14.81 m^3/sec (Figs. 9.7 and 9.8).

Before 1949, the total irrigated area covered 467,400 mu (1 mu = 666 m^2), of which 50% was irrigated by karez systems. In 1957, there were 1,237 karezes with a discharge of 17.86 m^3/sec and an irrigated area of 340,000 mu. At that time, members of a commune shared all duties related to their karez, including the extraction of sediment and general maintenance. The discharge thus slowly increased year by year, resulting in an increase in crop production and livestock.

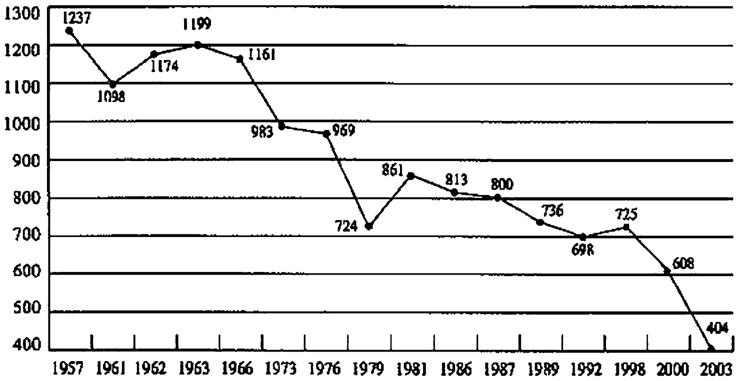


Fig. 9.7 Number of karez systems in the Turpan region. (Source: Karez in Xinjiang 2005)

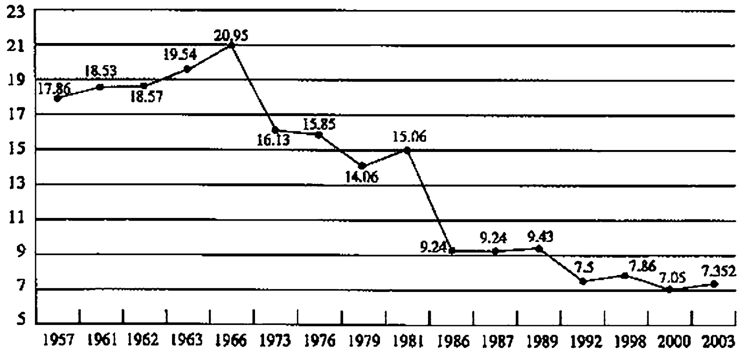


Fig. 9.8 Flow rate of karez in Turpan region (m^3/sec). (Source: Karez in Xinjiang 2005)

In 1958, the government started to construct 10 open irrigation canals in the area. As a result, the infiltration of water to the riverbed decreased. After 1970, when the use of electric pumping wells began, artificial resource management caused the water table to decrease, greatly affecting karez systems. For example, the Shen Ching people's commune had 69 karezes in 1961 with a discharge of 853 L/sec. By 1979, only 11 remained and the discharge was reduced. More recently, the commune has come to depend on electric pumping wells rather than a karez, but it has recognized the important role of the ancient system and has tried to keep those that are still functioning in good repair to meet the need for local production.

The land irrigated by a karez is usually flat and footpaths are narrow so water can be economized. In general, for irrigation, 80–100 m^3/sec is sufficient. A karez has no fluctuation of discharge, is not noticeably affected by seasonal change, and flows automatically without mechanical equipment, so the cost of water management is comparatively low.

9.4 Current Status of the Karez

Since 1995, research on karezes in Xinjiang has developed rapidly, and I have had several chances to discuss new angles of the karez study.[5] First of all, the planning and layout of a karez should be based on the overall planning of the water resources and hydrological conditions of the locality, harmonization with the economy, and social development and environmental protection. Water resources development in Turpan Prefecture briefly can be described as follows: diverting river water nearby for irrigation in the upper reaches of the river; abstracting water from the karez and pump wells for irrigation at the middle and lower reaches of the river; and building pump wells at the deeper portions of the karez to minimize mutual interference.

According to *Karez in Xinjiang* (2005), the decline in the use of karezes in the Turpan region is inevitable. However, the function of the karez in the ecosystem must also be taken into account when considering the future of the system. The karez was vital to the survival of oases in the past. Even today, it provides not only sustenance to humans, but also a suitable environment for birds and even aquaculture, forming a complete ecological chain to better rebuild a natural environment for people.

As a non-native researcher of the karez, I have not been able to engage in protection, restoration, or rehabilitation. However, I am very pleased to notice recent positive approaches towards—and robust interest in—the ancient systems in China, not only by the local government or institutions but by researchers from China, Japan, Europe, and elsewhere who recognize the importance of international collaboration and comparative study of other karez regions in furthering our knowledge about the systems.[6]

The karez has been a unique, traditional technique for water resources management in arid lands for centuries. Such a worthy cultural heritage should be maintained to achieve sustainable development of arid lands for the people living there for generations to come.

Notes

1. Further research has fortunately succeeded with very friendly collaboration between Chinese and Japanese specialists, and the first International Conference on Karez Irrigation was organized by the Xinjiang Institute of Biology, Pedology and Desert Research, the Chinese Academy of Sciences, and Meiji University.
2. A kanerjing uses groundwater, while a ching chhü uses river water.
3. I tried to get recent information for the distribution of karez in Xinjiang, but only data for 1963 were available. According to this information, four main centers of karez are Turpan, Shenshen, Hami, and Tuksun. For Urumqi, I could not get a positive reply for the existence of karez systems at present. For other oases of southern Xinjiang, field investigations in situ are necessary to confirm the small numbers of such systems. In other words, the exact information for all parts of Xinjiang could be obtained only on a local basis.
4. As a technical improvement in the construction of the karez, concrete tubing was first used in an underground tunnel in 1963. At Wushin people's commune, one karez (3,340 m in length with 144 shaft wells) irrigated 60 mu and had not required repairs for quite some time. In 1963, 40,000 workers installed about 2,300 egg-shaped tubes over a distance of 1,150 m, and the karez regained its former volume. From 1963 to the present (1981), there have been no accidents. Another partial improvement has been the use of a rectangular wooden pier to support the underground tunnel at certain points; this has also produced good results.
5. The most recent and monumental achievement by the initiative of the Xinjiang Karez Research Society in close collaboration with the Water Scientific Conservancy Research institutions of Turpan Prefecture and the Komul City Water Conservancy Bureau should be mentioned[0]. The publication, *Karez in Xinjiang*, consists of two volumes (Vol. I and Vol. II: 1,146 pages), including a completed inventory of the karez in Xinjiang with worthy illustrations and data. Without the remarkable two volumes, it is impossible to proceed with further karez research in Xinjiang.
6. I have had interesting discussions with an Omani scientist who is researching the falaj (similar to the karez) and several Iranian and French scholars. Chinese (including many Uygur), German, and Japanese scholars are trying to start joint research to analyze Turpan manuscripts in the Turpan Museum. With luck, we may find records of the origin of the karez in Turpan. In addition, technological innovations could help modernize karez construction techniques by, for instance, using advanced technology for the construction of large underground tunnels or digging the underground tunnel using a remote-controlled robot, although that may be an ambitious dream. Furthermore, using remote sensing and geographic information systems (GIS) technology, Japanese scientists are now going to analyze the geomorphological and hydrogeological conditions where karez systems exist.

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Chapter 10
An Introduction to the Khettara in Morocco: Two Contrasting Cases

Mohammed El Faiz and Thierry Ruf

Abstract On each side of the High Atlas in Morocco, various societies have built thousands of tunnel and well networks called khettaras, which are much like the qanats of Iran or the foggara systems of Algeria. Ancient writers have noted the ingenuity of these devices, but in the last 30 years, the use of khettaras has declined. An inventory is necessary to understand the rural zones where groups of khettaras still exist. The contrasting situations of the province of Marrakech (Haouz), where palm groves were irrigated primarily by hundreds of these underground tunnels, and the province of Tafilalet, where an inventory of 500 khettaras recently has been made, highlight the fate of the water management systems. Around Marrakech City, the collapse of the khettara is rapidly impacting water supply. In Tafilalet province, the situation seems more favorable for water supply sustainability and future use of khettaras, with 50% of the khettaras still "alive." However, the modernization of irrigation and the increase of wells are signs of change. How can these systems be maintained, and how can farmers be allowed to innovate without destroying what made the inhabitants of arid regions relatively prosperous?

Keywords Institutional · Irrigation · Khettara · Morocco

10.1 The Khettara: A Historical Overview

Beginning in ancient times, diverse societies on both sides of the High Atlas in Morocco built thousands of well and tunnel systems similar to qanats in Iran or foggaras in Algeria (see Chapters 6 and 8). These systems, called khettaras in Morocco, constitute a remarkable water management and delivery network that has enabled people to live in arid and semiarid environments. Comparing two areas of Morocco that have the highest number of khettaras—Marrakech and Tafilalet—reveals important differences in the management and use of water. Marrakech (Fig. 10.1) is

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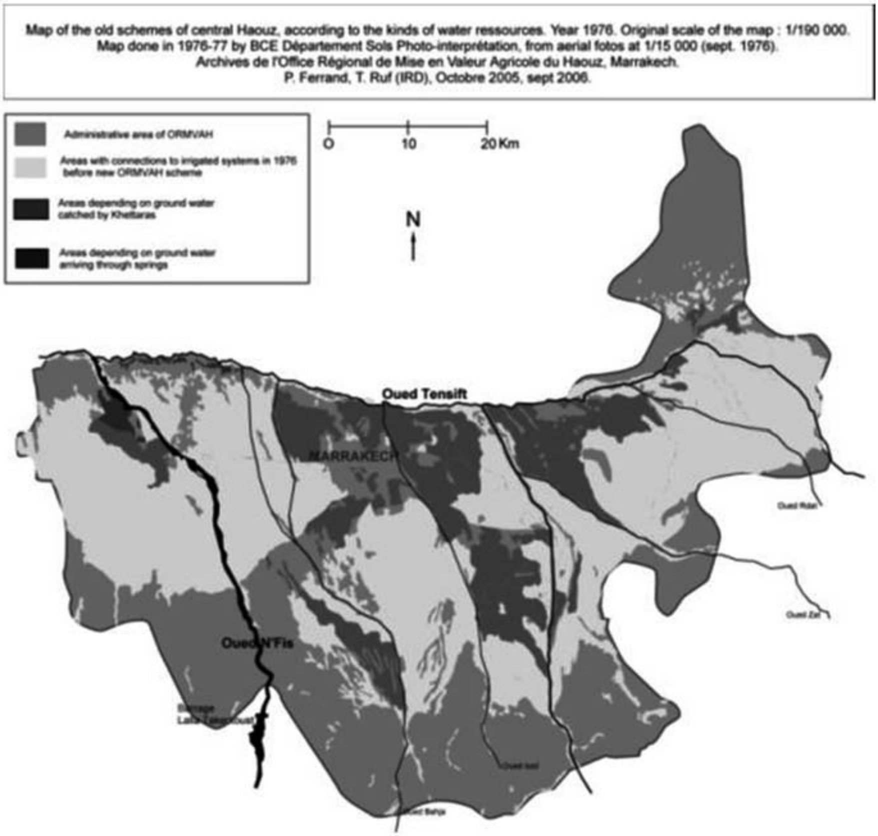


Fig. 10.1 Khettaras around Marrakech within the hydraulic area of Haouz

characterized by interlinked zones around a central palm plantation, with khettaras organized on the interfluves of the rivers N'fis, Baja-Rirhaia, Issil, Ourika, Zat, and Tensift. Tafilalet uses khettaras in outlying areas and also in central systems that draw water from rivers (Fig. 10.2).

The ingenuity of khettara systems has been recorded by old and modern authors in various areas of the world (Barcelo 1983; Chebri 2004; Hussain et al. 2008; IFAP 2005). Scholars disagree about how khettara technology was first introduced to Morocco, but the systems have been used there for centuries, if not longer. In Marrakech, the first record of khettaras dates from the founding of the city more than 900 years ago (El Faiz 2002). In Tafilalet, some researchers hold that the systems existed in the city of Sijilmasa before the eighth century AD (Oliel 1994) (Fig. 10.3). Various authors testify to the historical importance of the khettaras in local oasis development (Kabiri et al. 2003). Some are interested in the limited water resources and questions related to the protection of water harvesting zones (Jarar et al. 2004).

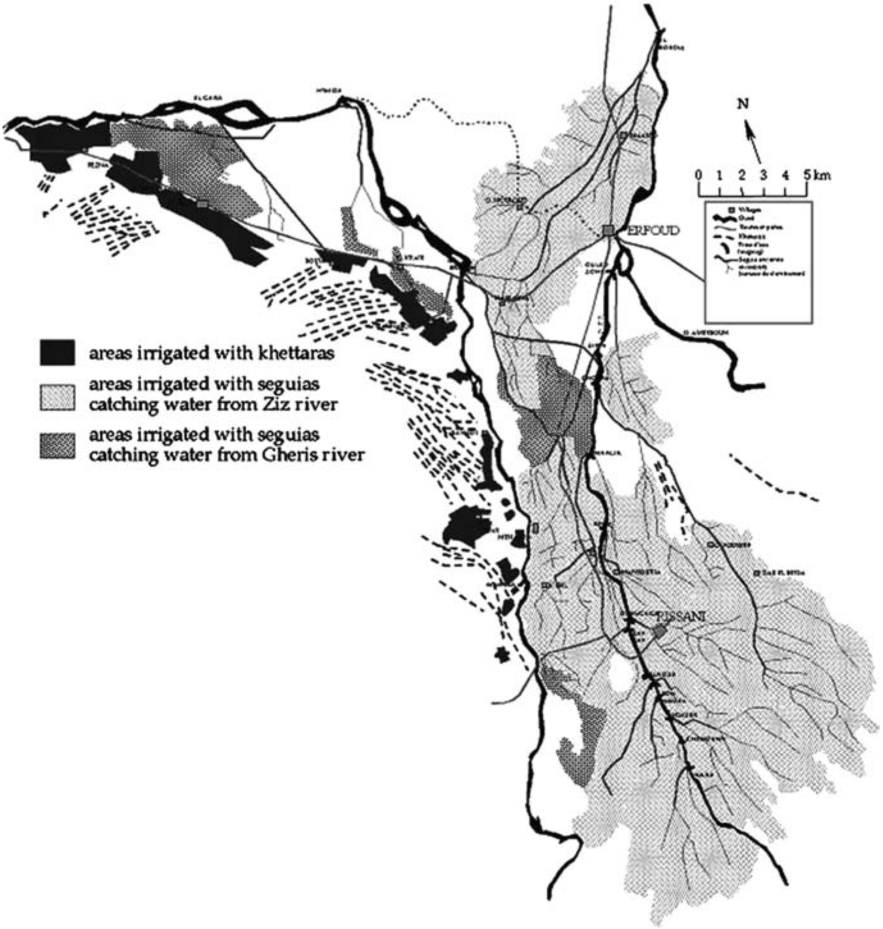
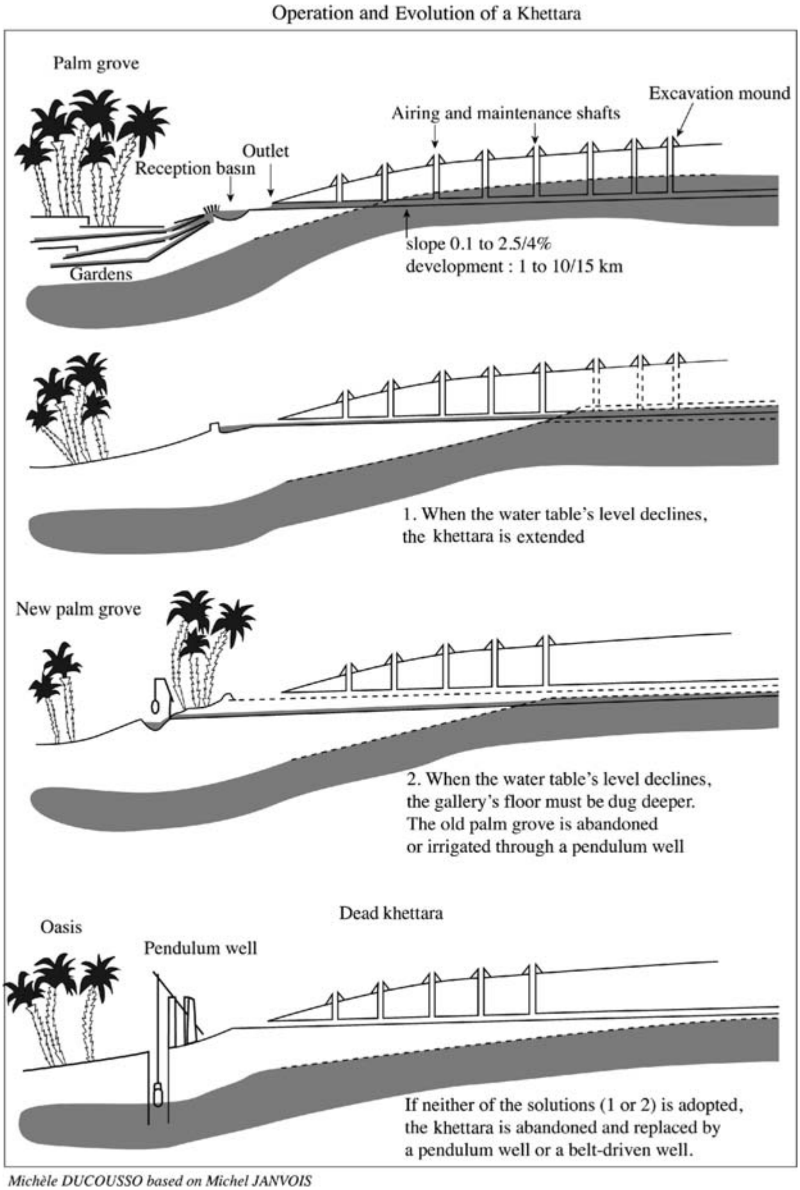


Fig. 10.2 Khettaras of Tafilalet within the hydraulic oasis area. (Source: El Faiz and Ruf 2006, based on ORMVA-TF-SCET 1983. "Plan directeur de mise en valeur agricole du Tafilalet" Vol. No. 9, Rapport de synthèse)

Hundreds of khettaras have been built around Marrakech. In 1970, 567 khettaras were registered by the water administration, and 500 were still working at that time (El Faiz 2002). They provided approximately 5 m^3/sec for 20,000 hectares (ha). Each khettara delivered on average 10 L/sec per 40 hectares. According to the maps that were published between 1940 and 1950 and those that were published by the Regional Office of Agricultural Development of Haouz (ORMVAH) in 1960–1970, khettaras primarily irrigated the palm plantations in the great periphery of the city and the royal gardens of Marrakech. They also provided water in districts inside the Medina (the old city) (Figs. 10.4 and 10.5).

Several khettaras in the south and in the west of Marrakech have been studied closely (Fig. 10.6). In 1975, the irrigation system of the N'fis River constituted a



Michèle DUCOUSSO based on Michel JANVOIS

Fig. 10.3 Installation of a drainage canal. Ducousso, M. (based on Janvois, M.): http://zoumine.free.fr/tt/sahara/sahara.html

composite whole of interlaced networks. It appears that these khettaras were organized in successive systems (El Faiz and Ruf 2006). From the south of the village of Tamesloht to the banks of the Tensift River, six large sets of khettaras shared by farming communities are still detectable as part of a repeated plan. First, a water collection area existed in the piedmont of the Atlas. Water was transferred

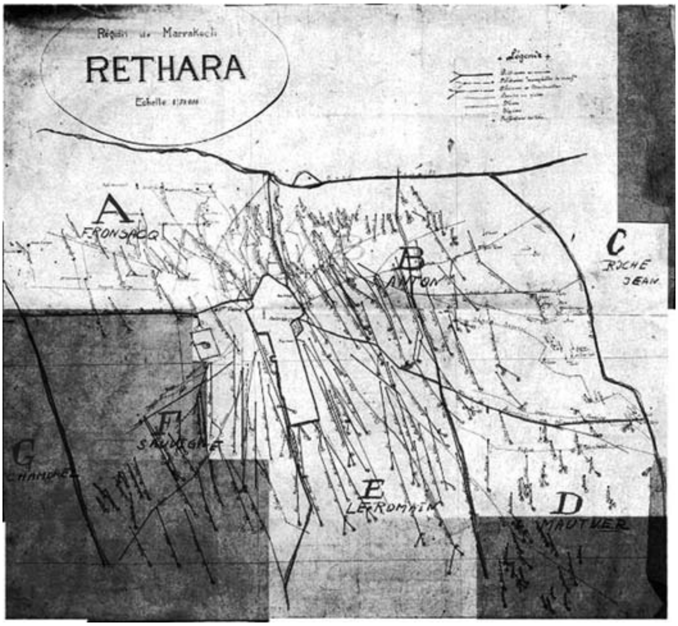


Fig. 10.4 Map of the khettaras of Marrakech in the periphery of the town – Original

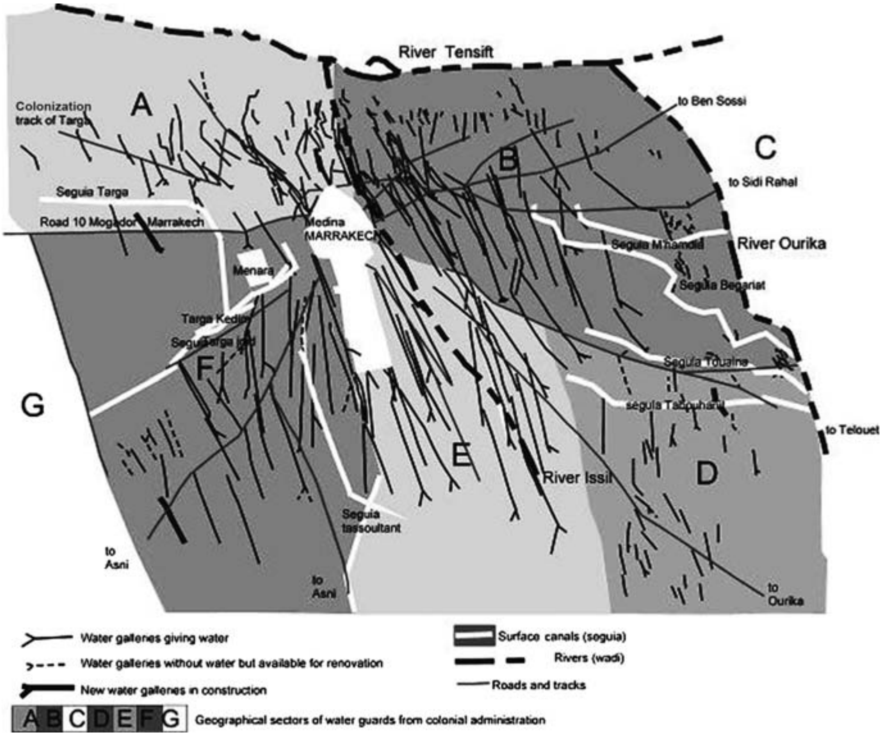


Fig. 10.5 Map of the khettaras of Marrakech in the periphery of the town – Interpretation

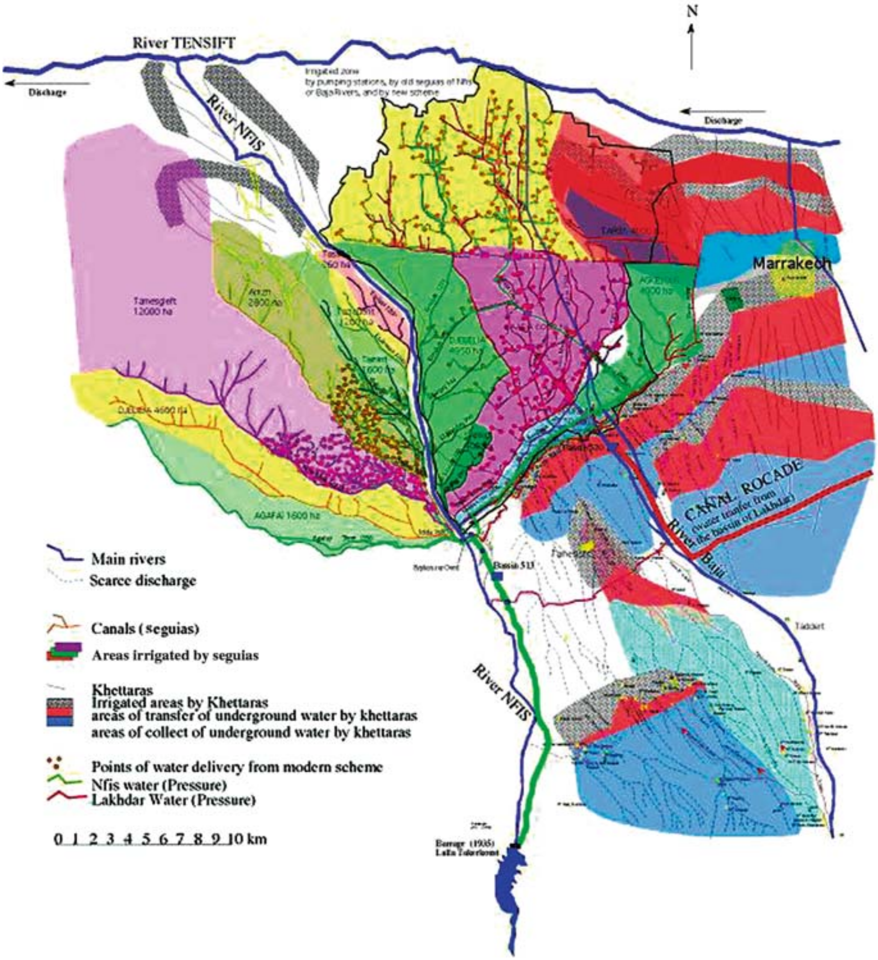


Fig. 10.6 Organization of the khettaras in central Haouz, west Marrakech. (Most of the seguias still run, while most khettaras are out of order) (Source: ORMVA Archives) (See also Plate 11 on p. 342 in the color plate section)

by dozens of tunnels towards open-air tanks, which enabled the downstream watering of nearby crop lands. The water losses of the irrigated area of the first unit fed the collecting area of the second set of tunnels. Then came two parallel tunnels: the main one was located on the bank of the desert escarpment of Tamesloht. This series fed the east portion of the palm plantations of Marrakech. Two other alignments of khettaras are also visible between the city itself and the bed of the Tensift River, which runs approximately 7 km north of the Medina. The recharge of the water table in the collecting areas also depends on the contributions of seguias (canals), which derive water from rivers like the Wadi Baja, which is itself an extension of the Rirhaia River in the plain of N'fis.

Therefore, an intensive use of water channeled through khettaras appears in successive rows with hydraulic interdependences, which characterize the surroundings of Marrakech. Technical and administrative records of irrigation services between 1950 and 1970 reveal the attention of the managers to conserve the khettaras, update the registers, monitor the performances of the main khettaras, and help arbitrate conflicts between people using the same khettara system. The records also contain several authorization requests to build khettaras in specific zones up until the 1960s, proof that the technique then was well adapted and anchored in local hydraulic cultures. Extensive records relating to the decline of khettaras in most other zones date to the 1950s.

What led, then, to the decline of the khettara system around Marrakech? As technical, social, cultural, and traditional systems, khettaras are inherently complex, and different stakeholders hold different views on what caused the collapse. Water engineers, who prefer modern technology, have argued that drought caused the decrease in water tables. On the other hand, community-organized farmers and researchers, who are interested in preserving cultural heritage, have said over-pumping is to blame. Yet another factor is institutional management: private landowners, the government, and farming communities were managing the systems and competing, without establishing any formal agreements to safeguard the khettaras (see Chapters 6, 8, 9, and 13). This stands in contrast to the people of Tafilalet who have worked together to conserve their own khettaras.

Old records attest to the existence of many khettaras in Tafilalet. When Morocco became a protectorate of France in 1912, the French administration surveyed native water management techniques to prepare water resources for new settlements. An organized and systematic inventory of the systems was finally drawn up with Japanese cooperation from 2003 to 2005 (JICA 2003). Several hundred khettaras are also registered in the province, including the sites of Ferkla, Errachidia, and Taouz; Jarar Oulidi et al. (2005) counted 386 khettaras, including 138 in the periphery of the plain of Tafilalet (Jorf-Rissani). Unlike the system in Marrakech, khettaras in Tafilalet follow a parallel layout and seem less dependent on one another (see Fig. 10.7).

However, the water flow through khettaras has begun to diminish; this general tendency in this oasis area seems related to the dryness that prevails rather than to the over-exploitation of the water tables. The government of Tafilalet and some nongovernmental organizations support drillings in some places, while private landowners definitely prefer them. Yet, drilling continues upstream of Jorf and, in some zones, downstream of the oasis of Bouia (El Baali et al. 2002; Ruf and Bouaziz 2005). This continuous drilling endangers the “living” khettaras.

10.2 Death—and Survival—of Khettaras

In the last 30 years, the khettara systems have had an increasing number of problems and will eventually disappear (El Faiz 2002; Kabiri 2005). Around Marrakech, the collapse of the system is causing several problems: the collecting fields of the

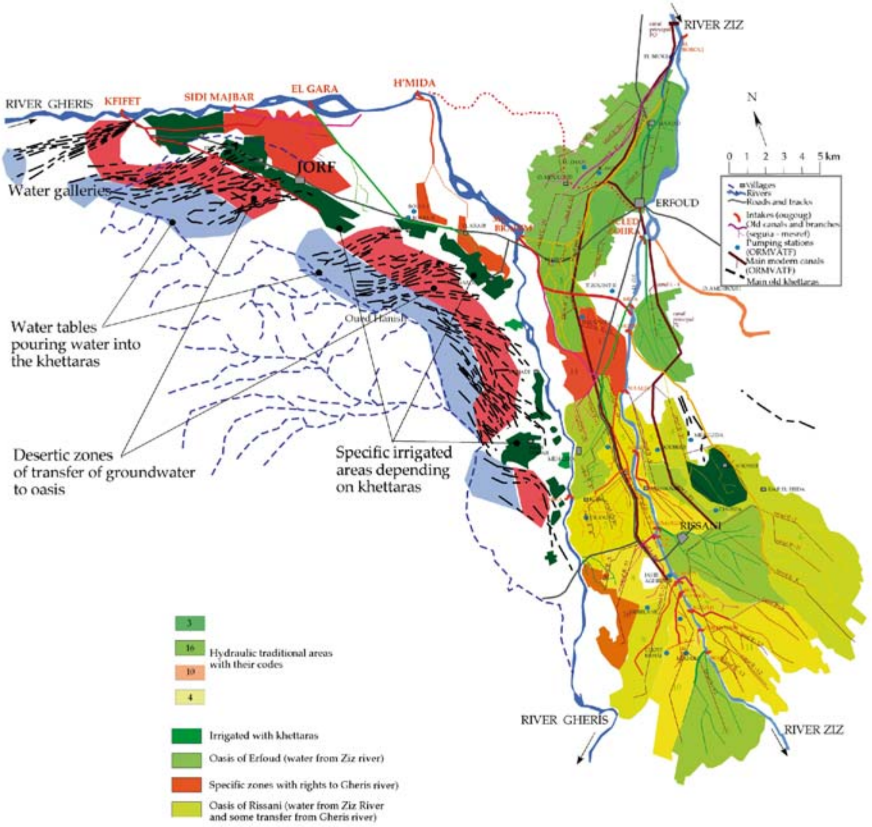


Fig. 10.7 Organization of the khettaras in Tafilalet province. (Source: Thierry Ruf 2008, based on ORMVA-TF-SCET 1983. "Plan directeur de mise en valeur agricole du Tafilalet" Vol. No. 9, Rapport de synthèse) (See also Plate 12 on p. 343 in the color plate section)

khettaras are over-exploited by drillings and private pumping stations; the rural districts irrigated by khettaras are becoming increasingly urbanized and are losing their links to the old structures, water, and users' solidarity; and a few khettaras function with very small flows, including those upstream of Tamesloht.

One of the essential questions for the future of khettaras is to understand not only the historical process of their construction and their appropriation by farmers, but also the process of abandonment. Climate and nature are not the only relevant factors. In addition to the arid conditions and the negative impacts caused by drilling, questions of social organization and institutions also play a role in the disappearance of khettaras. It is necessary to clarify the dynamics of the "extinction" of the systems or, at least, the dynamics of their abandonment, deterioration, or lack of maintenance, which seems to have accelerated between 1960 and 1970. The southwestern sectors of Marrakech are a good example of the disconnection between the government and the community based on joint work (touiza). The zone of Tamesloht still receives water through some khettaras, such as the Bougdira khettara, also sometimes called Khardali. The two names have been used, but according to the documents and maps found in the archives, the Khardali khettara dried out in 1950.

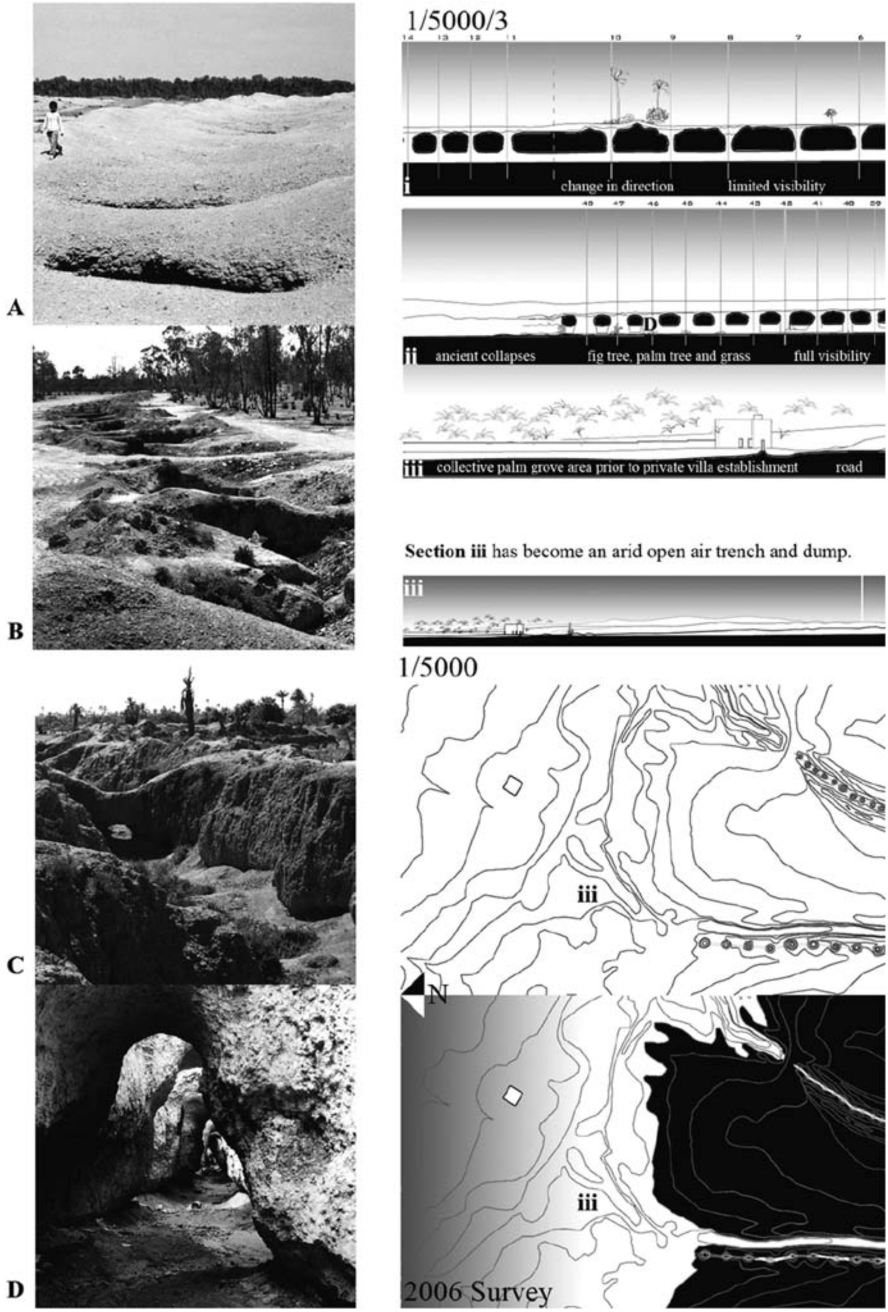
In this sector, three associations were impelled by the Office of the Haouz to manage the khettaras: Aïn Mssa, Tamguelfa, and Lemliz. These khettaras provide their users access to a small water flow (less than 10–15 L/sec) to irrigate olive tree plantations. The office helped only once to clear out the khettaras.

Abandoned khettaras have become an issue in Marrakech, where thousands of shaft holes are still visible in areas that once were rural but since have been consumed by urban sprawl. Architect and town planner E. Sors (2005) proposed to reinstate these abandoned systems in the town planning of greater Marrakech. The obsolescence of this mode of water supply justifies neither its dissimulation nor its destruction, but instead its reassignment and transformation. The proposal (Fig. 10.8) suggests the khettaras should serve as interfaces between the city and the countryside to restore the groundwater table as well as the indigenous plantations that suffered from its reduction. The wells could become natural water treatment plants for isolated homes or for entire districts in the vicinity of abandoned khettaras on the condition that collective water management among the city (consumer/polluter), khettara owners, and the eventual consumers of a renewed flow is actively and lastingly reactivated.

In Tafilalet, the situation of the old irrigation systems seems more favorable: nearly 50% of the khettaras are still perennial in areas that don't face pressures of urbanization. The studies that were undertaken recently on the oasis of Bouia, near Jorf, illuminate the essential social and hydraulic characteristics that the system of khettaras brings (Mbarga and Vidal 2005). The 75 families of the village have two working khettaras out of four that exist. The two inactive khettaras dried up decades ago with the encroachment of sand dunes. But the two others, the old one (qdima) and the new one (jdida), each provide significant, uninterrupted flows of 20 L/sec. Thanks to this regular contribution, the oasis of Bouia is permanently irrigated; floods provide a secondary source of irrigation, while a diesel pump downstream provides groundwater. Without these regular supplies, life for the families in the area would be much more precarious. This model of a local community of irrigators who control the resources significantly differs from that of water management at larger scales, where distribution is sequential and hazardous because hydraulic insecurity reigns. This is the case on the plain of Tafilalet, which depends on discharge from the Ziz River through a dam controlled by the water administration.

10.3 Tlout (Reviving)

The villages that preserved the khettaras are small islands of prosperity, while the remainder of the oasis is undergoing a severe hydraulic crisis. However, the modernization of irrigation and the installation of drillings raise several questions: How can these systems be preserved, and how can the local human societies be allowed to innovate without destroying what made the inhabitants of arid regions relatively prosperous? In Jorf, all the khettaras are managed by local institutions; users meet,



Section iii has become an arid open air trench and dump.

Fig. 10.8 Morphology of a buried water device in Marrakech's palm grove: Khettara Bel Kamel

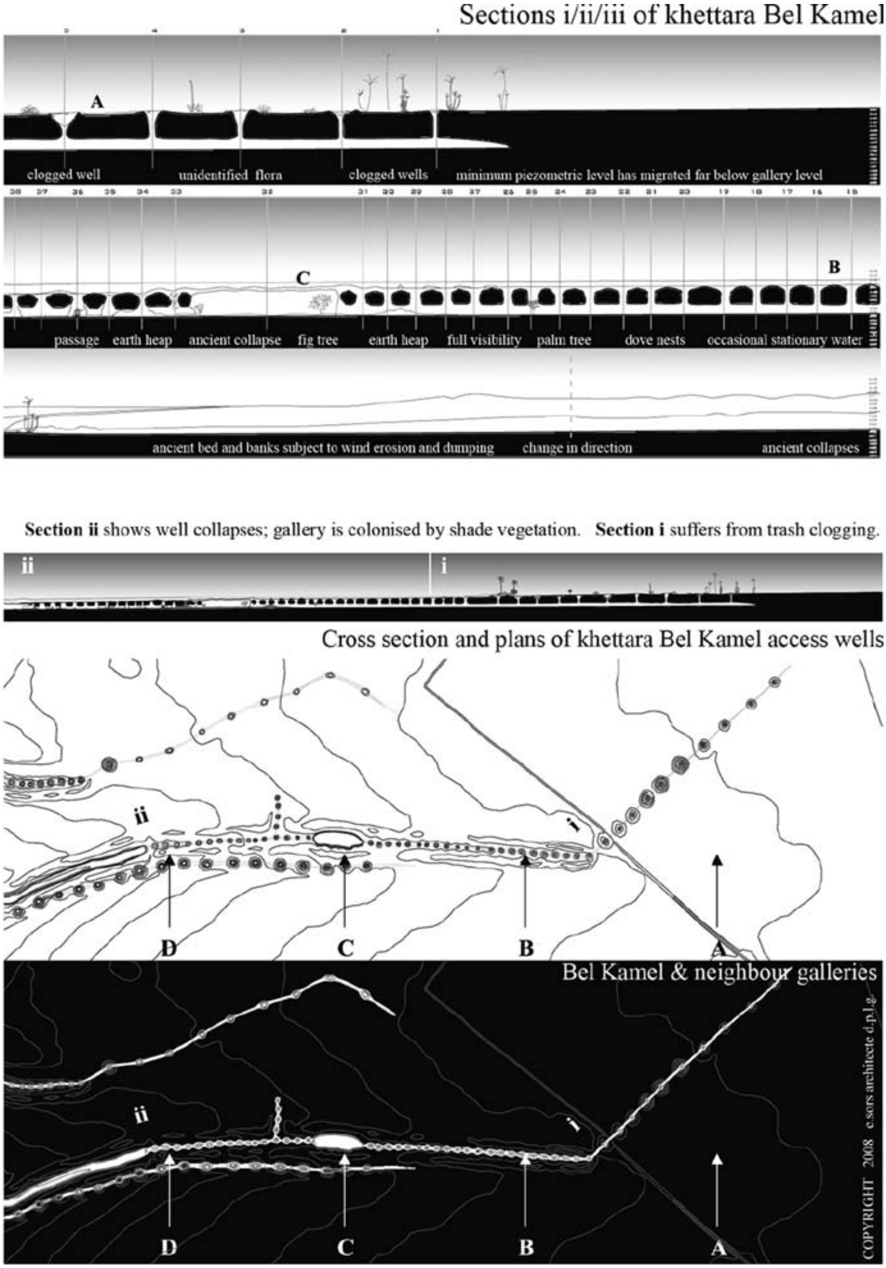


Fig. 10.8 (continued)

elect chiefs, and organize the joint work and the water schedule. Because of the return of rain in Tafilalet since 2005, water tables are rising, and many communities are acting collectively to resurrect the khettaras. More than 20 khettaras are now working again for hundreds of small farmers. The old khettara chiefs share with a new, young generation the responsibilities of managing the ancient systems. They say, "Tlout," to explain what is happening. Tlout means "reviving."

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Chapter 11
Digitally Conserving an Endangered Built Heritage in Kashgar, an Oasis City of the Taklimakan

Michel Florenzano, Marie-Françoise Courel, and Francesca De Domenico

Abstract The ancient oasis city of Kashgar sits at the intersection of caravan routes that once made up the Silk Road. Located west of the Taklimakan Desert in western China, Kashgar has been able to survive due to efficient management of water reserves and maintenance of canals that irrigate crop fields and provide subsistence for local inhabitants. Water has a central role both in the organization of inhabited spaces (urban or rural) and in the distribution of domestic spaces. Indeed, the vernacular architecture of the city is particularly well adapted to the area's hyper-arid environment. Over the last 20 years, however, the city has undergone major urban development and reconstruction, a phenomenon that has threatened its architectural heritage. A digital method has been designed that makes it possible to record images of an architectural ensemble and thereby conserve a particular "culture of construction" that is endangered in Kashgar.

Keywords Architecture · Aridity · Conservation · Heritage · Water

11.1 Kashgar: A Brief History

The storied city of Kashgar (Kashi in Chinese) sits at the intersection of two caravan routes that once made up the ancient Silk Road, at the foot of the Pamir and the Tian Shan mountains in the Tarim Basin of western China. Its history stretches back more than 2,100 years, spanning the Western Han (206 BC–24 AD) and the Qing (1644–1912) dynasties. Kashgar was the main political, economic, cultural, and religious center of western China, and the huge Kashgar oasis encompasses several villages that once hosted royal courts and military garrisons.

Throughout its rich history, Kashgar, thanks to its geographical location, has been a meeting place for different cultures and religions. During the Middle Ages, many

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G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
DOI 10.1007/978-90-481-2776-4_11, © Springer Science+Business Media B.V. 2010

scholars, artists, and artisans settled there, contributing to its intellectual, artistic, and commercial reputation. In the tenth century, Kashgar became an important Muslim center, and Islamic influences can still be seen, especially in the city's architecture and urban layout.

During the last 20 years, rapid economic development (mining, oil, agriculture, etc.) has prompted a sharp increase in the region's population and, consequently, urban renovation on a massive scale. With exceptions such as the Id Kah Mosque—one of a number of outstandingly beautiful mosques and mausoleums that have been conserved and renovated—the original character of the city is, inexorably, disappearing. The old neighborhoods, with their narrow, winding streets lined by laterite mud houses with carved wood balconies, are a thing of the past. The picturesque lanes have given way to straight, wide asphalt roads that go around and into the Old Town, and modern houses now stand where their one or two-story mud-walled forebears once were. Kashgar's remaining examples of Uygur, a Turkic people of Central Asia, architecture are threatened with oblivion. To help conserve the city's built heritage that has evolved around water, the Project for Digitally Recording the Architectural Heritage of Kashgar establishes the principal methodologies to be used in the digital recording of vernacular architecture, from the acquisition of data to their use in a database.

11.1.1 An Oasis in the Desert: Kashgar

Kashgar has survived thanks to the efficient management of water reserves and the maintenance of the canals that irrigate the crop fields and provide subsistence for local inhabitants. In these windswept desert plains, where rainfall is low and variations in temperature are extreme (50°C in summer to –20°C in winter), survival was, and indeed still is, intimately linked to the presence of water. The ancient irrigation networks known as karezes are sophisticated systems consisting of vertical wells, subterranean and surface tunnels, and small reservoirs. Forced by gravity, melt water flows from the mountains, down the underground tunnels, and to fields and houses, where it is collected in surface tunnels to be used for irrigation. The karez system has several advantages: it reduces evaporation year round, limits water infiltration, and can be used to distribute a large and variable water supply (see Chapter 9). Furthermore, the system neither consumes energy nor causes pollution. This ability to distribute water resources was the cornerstone of the city's success and is, to this day, at the heart of trade and industry in the Tarim Basin.

11.2 Water Spaces

Without water, the Kashgar oasis would not exist. In the oasis, city, and countryside, water is the point of departure for urban layout and architectural composition. Depending on the kind of mark it leaves on the oasis's landscape—linear or punctual—and depending on the main purpose for which it is used (irrigation, domestic use), water gives structure to the inhabited space in different ways (Fig. 11.1). In the countryside, vegetation and dwellings skirt canals and ditches where water follows a linear course. In urban areas, on the other hand, water sources are often punctual (wells, cisterns). Consequently, dwellings and vegetation develop around such points in a concentric manner.

In inhabited areas, water occupies a public, community space—a pleasant place to be due largely to the cool shade provided by surrounding vegetation. In rural and urban settings, water spaces are located in areas that can accommodate a large number of people, thus facilitating access to the precious resource. The idea of a public space in which water can be shared has influenced local architecture. For example, in houses with interior courtyards, the courtyard is seen as a common area, a place in which families living in the surrounding apartments can gather. Often, in these flora-rich enclosures, a well or small basin provides water for the domestic use of nearby dwellings, and beds and kitchen equipment are often found there. Both on the banks of canals and in courtyards, the combination of water and vegetation (vines, fruit trees, etc.) contributes to protecting the environment, in this case the architectural environment. The network of streets and lanes also is adapted to water sources.

11.2.1 The Structure of the Inhabited Space: A Response to the Environment

In arid environments, human beings have to rely on their ingenuity. Drought, heat, strong winds, and daily and seasonal temperature fluctuations are typical characteristics of arid climates, which represent a threat to existence even when water is accessible. In order to strike the ideal compromise between the characteristics of the milieu and their day-to-day well-being, and to construct their living space accordingly, people are forced to make the best of all the resources at their disposal. Everything is adapted to the environment. Thanks to their extensive knowledge of the desert, local people have been able to build a made-to-measure habitat in which forms become functions. Thus, from urban planning to architecture, each new element added by people to their territory can be explained in reference to climatic conditions.

Most of the elements structuring urban space (narrow streets, covered passages, tenement-style buildings) and architecture (thick walls, terraced roofs, courtyards) are specifically designed to counter the heat. This urban and architectural configuration creates shade in the streets and reduces the number of walls directly exposed to sunlight, which means that houses are cooler during the summer months.

However, in rural areas, where there are many fewer buildings, the best protection against the sun is afforded by vegetation. Depending on the region, different types of trees are used to moderate the strength of the wind and reduce air temperature. In the Sahara, as in the Middle East, the tree most frequently used for this purpose is the date palm (*Phoenix dactylifera*). But in the rural villages of the Tarim Basin

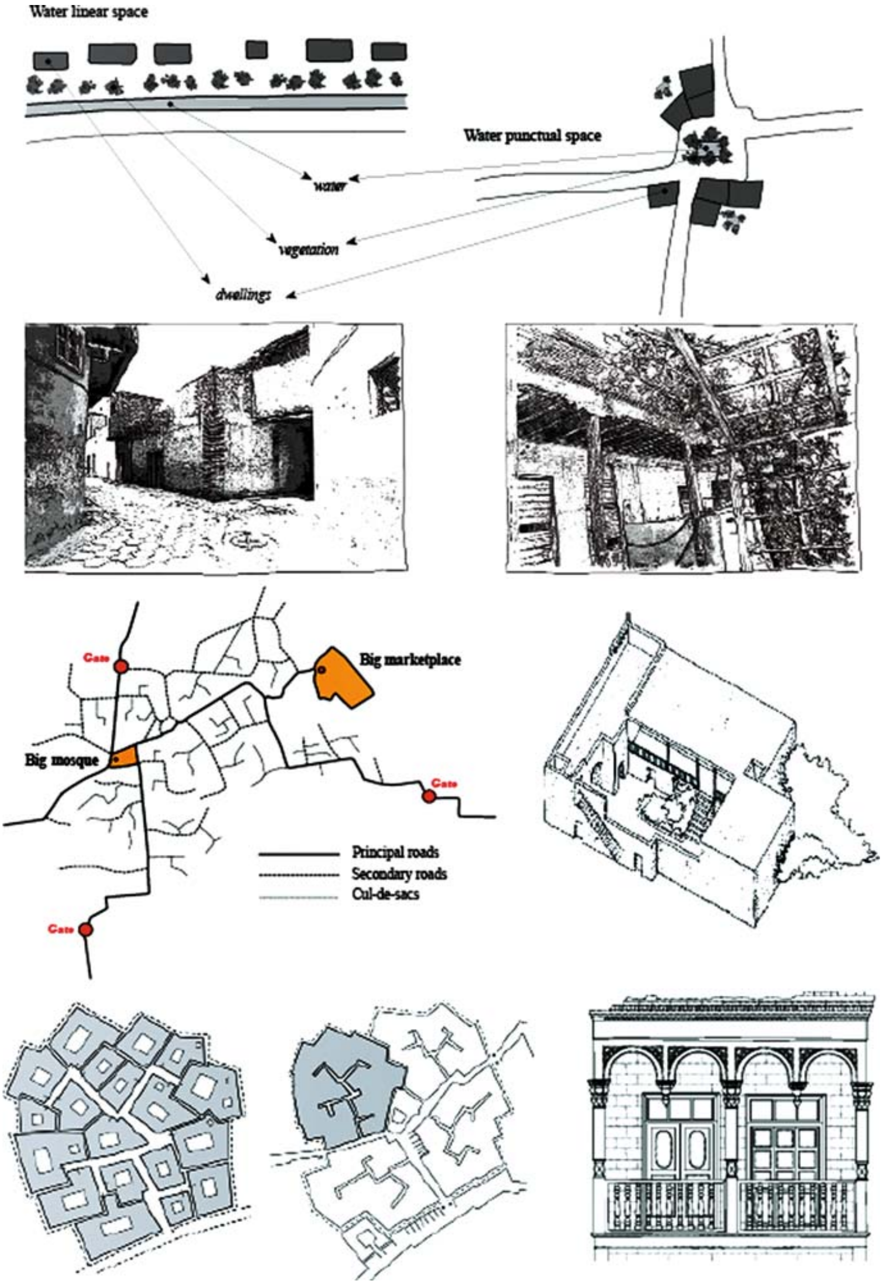

Fig. 11.1 Analysis of the relation between water, climate, and inhabited space from the town scale to the architectural scale

in Central Asia, crops and dwellings are protected from the sun by the Euphrates poplar (*Populus euphraticus*) and by vines.

Canal water increases the humidity of the air. This not only makes things more comfortable for people in their day-to-day lives, but also has a positive influence on crops such as cereals, cotton, and fruit trees. Likewise, vines, which are grown inside rural dwellings in Xinjiang, also have the effect of lowering the temperature. Planted in front of the main facade or in the courtyard and supported by wooden trellises, they offer significant protection from the midday sun.

Thermal comfort, however, is directly linked to the efficiency of the materials used. In arid and semiarid environments and in urban and rural settings, the material most often used in buildings is earth. Available in huge quantities across the globe, earth has a number of advantages. The isothermic and hydrothermic qualities of thick earthen walls make the inside of houses comfortable. On the other hand, such buildings are easily damaged by water and humidity and require constant maintenance. During the rainy season, facades are often leached, a process which inevitably makes them less stable. Another problem is that water with a high salt content can damage bricks at the bottom of the wall and potentially cause a collapse—another example of water influencing the lives of human beings, this time in a negative way. In spite of such problems, mud and soil continues to be used to build houses. By applying ancient expertise and traditional construction techniques, which are an integral part of the culture, the people of Kashgar have been able to create a veritable climatic system with surprisingly successful results.

11.3 Town Planning and Vernacular Architecture

In arid environments, the logic underlying urban planning and construction techniques is informed by the same principles. However, typo-morphological variants exist from country to country based on the specific characteristics of the region and local traditions. Any analysis of environmental characteristics (climatic, topographical, commercial, etc.) must take into account the historical and cultural context of the milieu being studied.

11.3.1 Urban Morphology and Architectural Typologies

In Kashgar, the historical importance of trade and Islam is reflected in the urban structure and architectural characteristics of the Old Town. The central market and the principal mosque are linked by the main streets of the Old Town, which lead into a dense network of ever-narrower and more winding secondary streets. These streets become increasingly chaotic as they follow the morphology and orientations of houses before finally petering out into any number of cul-de-sacs.

Located next to the river, Kashgar's main market is some distance from the Great Mosque. However, there are several ground floor shops in the heart of the Old Town, as well as in main streets and at the end of secondary streets ending in cul-de-sacs. Shops and artisan establishments are surrounded by residential areas. The fabric of the community is kept alive by a network of narrow streets, covered passages, and compact, densely inhabited neighborhoods. The trading activities and Islamic culture of the inhabitants are reflected in the city's exterior aspect. The configuration of the streets, the orientation of the houses, and the architectural typologies and methods of construction, depend to a large degree on climatic conditions and the availability of local resources. For example, the streets are concave, probably to prevent water from accumulating in front of earthwork houses vulnerable to infiltration and flooding. But there is a drawback: water flows away from the houses towards the middle of the street, causing damage to the road surface (degradation, cracks, dislodged flagstones, etc.).

The oldest buildings, which both border and shape these narrow streets, have interior courtyards, a typical feature of old Islamic cities. The layout of these buildings is often very irregular, as it is frequently dependent on the configuration and dimension of the interior courtyard. Such courtyards are a key motivator for the architectural fabric of the city (see Fig. 11.1). The configuration of these buildings, each one different from the next, gives the Old Town a typically chaotic look. However, the city's old neighborhoods still contain several examples of loggia-style buildings characteristic of the Uygur tradition. These buildings are equipped with balconies in carved, colored wood, with arcades, pillars, and balustrades featuring a profusion of different shapes and decorative elements.

11.3.2 House with Interior Courtyards

In Kashgar, houses with interior courtyards have one or more stories (two or three at most) and terrace roofs. Built of mud with thick, clay brick walls (raw or baked) and reinforced by a wooden structure, they are highly irregular in shape. The buildings share one or more walls and are often linked to each other at the first floor level by rooms that extend over the street, forming numerous covered passages (sabat) typical of oasis towns. The oldest walls are made of earth bricks with raw clay mortar. The small, parallelepiped bricks are usually either laid on top of each other or arranged in a chevron pattern. Rainwater runs off the terrace roofs and into the street via cylindrical or semi-cylindrical gutters. Where buildings have been partially renovated, unbaked bricks are used for the base of the walls. Sometimes there are openings leading to a veranda or terrace. Openings designed to let air into rooms are often hidden by beds supported by carved cylindrical columns.

11.3.3 Loggia-style Buildings

Loggia-style buildings can be found all over Kashgar, but the finest examples are located in the heart of the old Uygur neighborhoods and along the two main streets of the Old Town (see Fig. 11.1). These buildings, which are between two and four stories tall, are generally built next to one another on either side of the main streets. Loggias were originally designed as an extension to domestic areas. For the Uygurs, they serve as an extra room that can be used for eating, sleeping, or entertaining, or as children's playrooms. Due to the morphology and composition of the elements which constitute them, loggias are also a highly effective way of dealing with the heat. Long, covered corridors with shade-giving arcades, they generate gentle breezes which cool the interior of the houses. Nevertheless, loggias are vulnerable to climatic variations and tend to deteriorate fairly rapidly.

11.4 Digitally Recording the Built Heritage

In an effort to capture Kashgar's built heritage, the Project for Digitally Recording the Architectural Heritage of Kashgar[1] is designed to collect data (metric, typological, morphological, qualitative, etc.) on buildings to create a descriptive model of Kashgar's vernacular architecture that can be applied to each building, from its overall structure to its minutest details. These descriptive models will be entered into a database in which buildings are classified according to the typological and morphological characteristics of the structure as a whole (houses with courtyards, loggia-style buildings, etc.) and its component parts (number of stories, type of loggia, type of decoration, etc.). Quantitative and qualitative information (construction date, function, materials used, state of conservation, etc.) and specific resources relative to each building (photographs, scatter diagrams, global positioning systems, or GPS, coordinates, etc.) will be correlated with buildings whose details have already been entered into the database. An interactive map of the town featuring all the buildings in the database will then serve as a navigation tool that can be used to access relevant data.

11.4.1 Architectural "Morphotypes": Describing Emblematic Buildings

Starting in 2005, descriptions were produced using a method developed at Modèles et simulations pour l′architecture, l′urbanisme et le paysage (MAP). The method was based on two descriptive techniques, one of which uses digital photography, the other, laser scanning. The two techniques served as the basis for a geometrical and architectural model of the building in question. These techniques were tested on a sample of buildings belonging to two architectural typologies: buildings with interior courtyards and those with loggias. However, different approaches were used in different cases: laser scanning and scatter diagrams were used for architectural representation[2]; automatic meshing was particularly suitable for the "as built" geometrical reconstruction of buildings with a complex morphology[3]; and describing relevant profiles was the best method for describing the building as a whole.[4]

The shared functionalities of the geometrical modelization software programs made it possible to trace lines and curves in space and to generate volumes either by extruding or revolving the profiles or by deforming geometrical primitives. Three-dimensional reconstructions of the building can be used to obtain plans, cross sections, digital filaria models, etc.[5]

The multi-image photographic description technique was tested on all the loggia facades of a sample of buildings located in the main streets of the Old Town to identify the typological variants of the architecture. The strategy used was mainly based on "scale readings" and on "multi-image blocks" of the building concerned. A systematic photographic description of the building was carried out at various levels of detail: the building in its urban context, its facade, the loggia, the composition of an individual loggia, and its decorative elements. Using this approach, the photographs were classified and entered in the database, linked to the building concerned and/or to a part of the building (facade, loggia, part of the loggia, etc.) in an unambiguous fashion. The number of photographs and the ways in which they were taken varied according to the hierarchical group in question.[6] Using blocks of images and taking a number of reference measurements (heights of doors and windows, etc.) allowed us not only to archive a large number of photographs in the database, but also to ensure that we could access metric and morphological details from individual images.

Thanks to photogrammetric restitution techniques based on calibrated block images, we were able, after entering the dimension references, to generate new references based on coherent projections obtained by means of calibrating the cameras (Fig. 11.2). Calibration consists of establishing spatial relationships between the lenses of the cameras, the points on the photographs, and the spatial coordinates. By calibrating the first eight points and correlating them with all the photos in a block of images, we could extract other spatial coordinates using a selection of correspondences between the photos. The result was a scatter diagram describing the essential geometrical nature of the facade in space.

The scatter diagram can be used at any time to obtain the dimensions of both the building and its individual components. It can also be used to generate a three-dimensional reconstruction of the object represented and visualize complex images. The approach generates a large number of different representations which vary according to the uses to which they are to be put (photo models, facade designs, decorative elements, etc.).

11.4.1.1 The Photographs

For recording the building in its urban context, the camera used (One Shot 360) generates a 360-degree panoramic image in a single shot. Photographs of this kind are particularly useful for documenting the relationship between individual buildings and the urban fabric as a whole.[7] We developed a method of extracting multi-image blocks of the building and its component parts[8] because we needed to be able to obtain, in a rapid and flexible fashion, information that can be used in

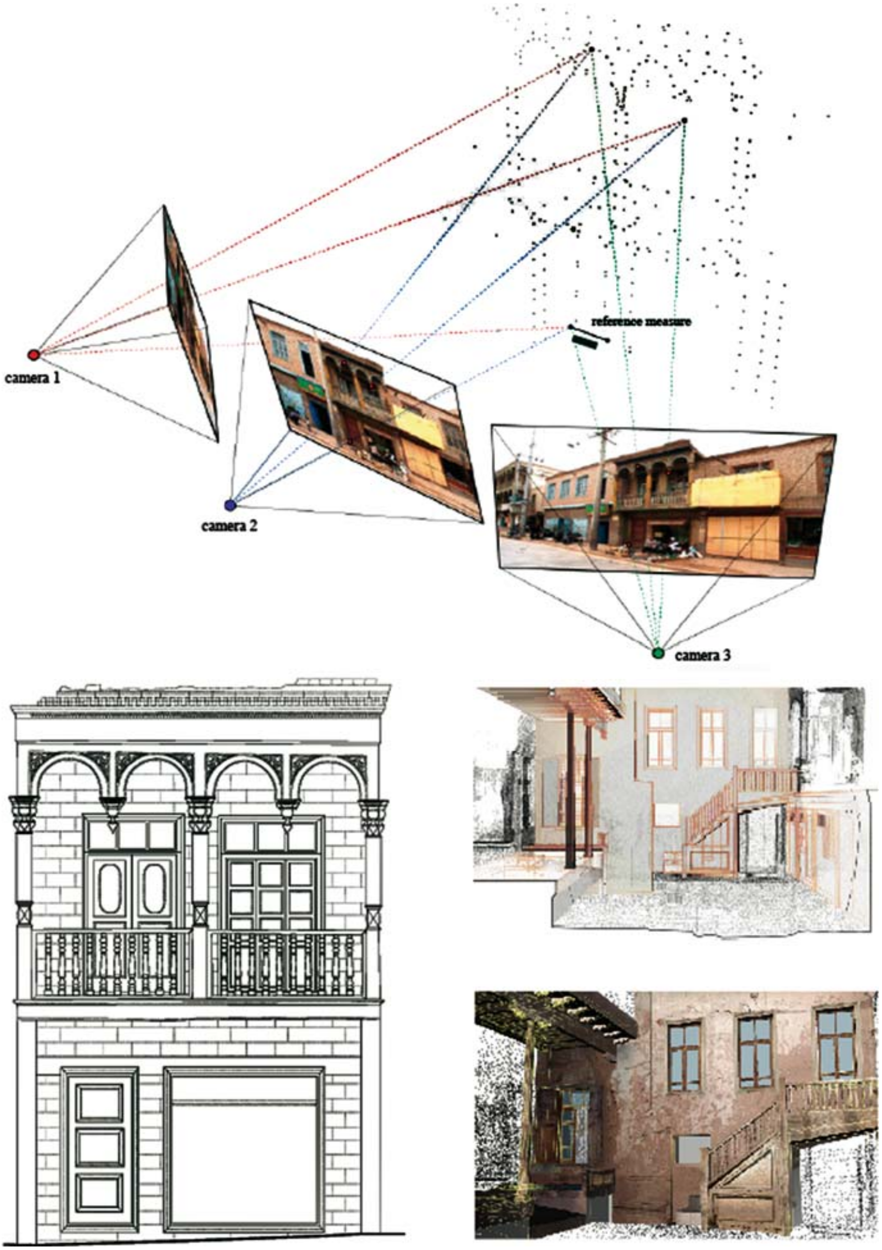

Fig. 11.2 Three-dimensional (3D) laser scanning and photogrammetric techniques applied to surveying inhabited spaces in Kashgar

the visualization phase. In so far as decorative elements are concerned (friezes, bas-reliefs, etc.), only one face-on photo was taken of the object to produce modified visualizations. The system of coordinates obtained in the preceding stages of restitution enabled us to obtain at least four points to be used to calculate the homography.[9]

11.4.2 The Recording and Valorization of Architectural "Morphotypes"

We have worked towards developing a database capable of hosting, categorizing, and visualizing different types of information, resources, and knowledge associated with the architecture of Kashgar. In order to test the efficiency of the database, we focused on studying and classifying attributes relative to the typology of houses with loggias, particularly the attributes of the facades. On the basis of observations and descriptions made in situ, we attempted to identify a method for describing the buildings that would express the architectural specificities and variants of this typology and be compatible with the hierarchical structure that we wanted to give the database to ensure that the content was semantically coherent.

The database contains three different groups of data: general information about individual buildings, documentary resources, and information about the typology of individual buildings (Fig. 11.3). General information about individual buildings enables users of the system to pick them out in the map of the city. The data recorded in the corresponding buildings table are, in effect, the buildings' identification: the name and number of the street on which they are located, their function, their GPS coordinates, etc. Other data concerning the history of the buildings (construction date, owner's name, etc.) also are included.

Documentary resources include all the "external" data associated with a particular building (photographs, sketches, documents, etc.). We will be able to add a table for every two- or three-dimensional representation of a building to the existing table of photos and the scatter diagrams. We are considering using two formats available free on the Internet: SVG for two-dimensional representations and Virtools (free for a limited trial period) for three-dimensional models.

Information about the typology of the buildings, which is at the heart of the conceptual modelization, concerns attributes specific to a particular typology. A building's typology is broken down into "descriptors" organized into "groups" used to describe the characteristics of the buildings. The data are organized hierarchically according to the scales of analysis used. We were thus able to obtain a complete list of all relevant scales of analysis and architectural variants of traditional Uygur structures, from the building itself to the smallest details.

We decided to focus on recording data concerning buildings with a loggia. The descriptive model we adopted includes four tables that enable us to perfect our knowledge of the typology as we add information. The typologies (for example "with a loggia" or "with a courtyard") are to be found at the first level of analysis.

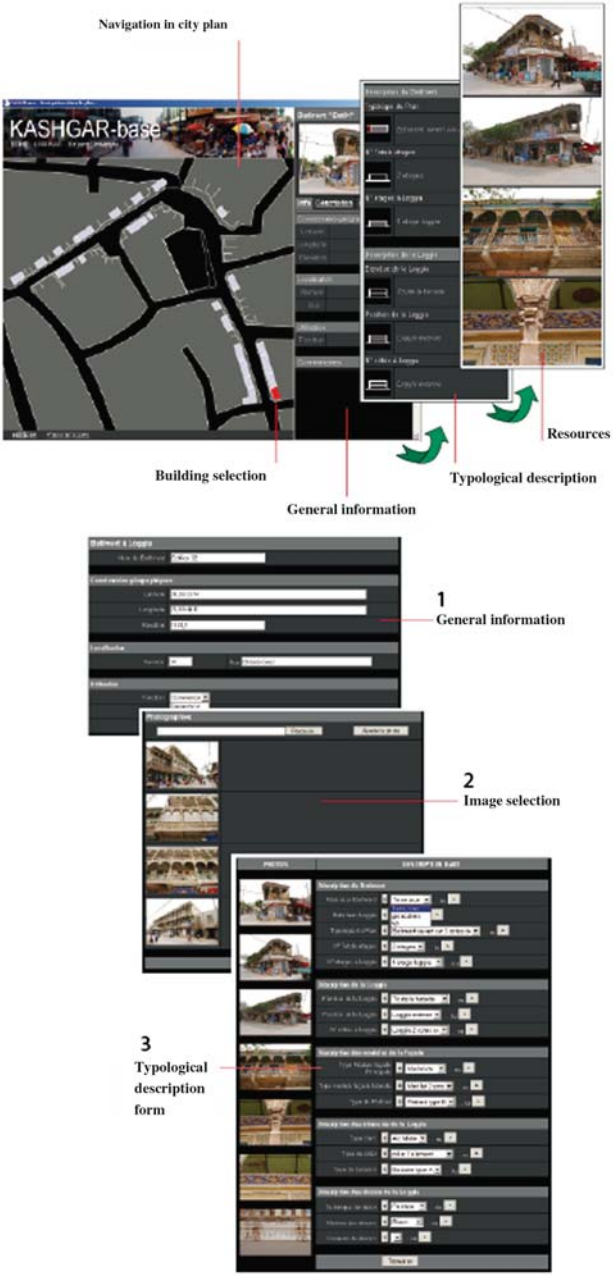

Fig. 11.3 Screenshots of the information system developed: navigation interface and data insert form

At the second level we find "groups of descriptors" or "families" of a particular building function (loggia, decorative elements). At the third level of analysis, we find the "descriptors," specific aspects of an element (the shape of a loggia, a type of pillar, etc.). Finally, the last level includes "types observed" relative to the descriptors in the level immediately above (a loggia with two arches, geometrical motifs, etc.). These tables enable us to use the database to study a typology rather than an individual building.[10] In practice, these tables represent all of our knowledge about a particular typology. As we add new entries to the tables (e.g., a new type of arch, a new material, etc.), we increase our general knowledge about the typology.[11]

11.5 Conserving the Memory of an Oasis City

A key motivator in the urban and agricultural areas within the oasis, water provides humidity and protection for people and crops against excessive heat. Climatic town planning and architecture (irrigation canals, the layout of villages, building techniques, etc.) contribute significantly to maintaining the kind of balance between people and the environment that characterizes oasis-based societies past and present.

High aridity and accelerated urban development are jeopardizing Kashgar's traditional architecture, and urgent action must be taken to save it. In the case of Kashgar, laser and photographic descriptions have enabled us to collect a large amount of information on the characteristics of Uygur architecture, from the use of geometrical motifs to the conservation of materials. These digital tools have demonstrated their ability to protect, conserve, and enhance the memory of a culture, which, through its architecture, reflects its reach and its ability to adapt to a hostile environment.

Notes

1. A joint Franco-Chinese project signed in 2005 by the University of Xinjiang and the l'École Pratique des Hautes Études. Among the project's scientific partners were Interdisciplinary Research Unit 694, MAP Modèles et simulations pour l′Architecture, l′urbanisme et le Paysage; Interdisciplinary Research Unit 8586 PRODIG (CNRS/University of Paris 1, University of Paris VII, EPHE), and the Mission de la recherche et de la technologie et l'Institut "ressources, environnement et sciences de l'information."
2. We used a flight-time scanner, which provides a very precise description directly expressed in three dimensions. The surface area of the buildings described was represented by spatial coordinates. This long-range technique (between 2 and 200 m) measures the horizontal and vertical angles of a laser beam and calculates the distance between the laser and the impact point up to 5,000 times a second. However, there are some disadvantages: external "obstacles" (trees, posts, other buildings, etc.) can get in the way of the laser beam, preventing it from hitting the surface of the building at which it is aimed, and creating shadow zones in the scatter diagrams. In order to avoid this, a number of lasers must be set up around the building in question. They will then be consolidated to obtain a scatter diagram of the entire building. The scatter diagram is generally very heavy and hard to manipulate in three-dimensional modelization software. However, scatter diagram processing techniques have been developed

with a view to producing lighter files and making the geographical representation and morphology of the building described easier to read. In Kashgar, three laser scan description tests were carried out: a description of the main facade of a building with a loggia; a description of courtyard-facing facades in a large building that was being demolished; and the complete description of a building with an interior courtyard. We used the latter to study the morphology and organization of buildings characterized by this particular architectural typology. The complete scatter diagram of the house with a courtyard is made up of three million coordinate points. Two scatter diagram processing techniques were used: automatic meshing for the architectural elements, and relevant profile extraction for the three-dimensional reconstruction of the building.

3. For example, the details (arches, pillars, etc.). A triangulation technique that converts the points of the scatter diagram into a coherent polygonal model (mesh).
4. This method consists of the manual, three-dimensional reconstruction of the buildings from a selection of scatter diagram points. Using this technique, profiles can be identified and the buildings reconstructed.
5. A number of laser scans were carried out at various levels of detail. A 10-cm mesh for the entire building; a 1-cm mesh for a loggia module, and a 5-cm mesh for each detail (capitals, pillars, arches, etc.).
6. For the building in its urban context (one photo taken with One Shot 360)

   - For the building's facade (one block of three or five photos taken with a 20 mm lens)
   - For the loggia (one block of three photos taken with a 35 mm lens)
   - For the loggia modules (one block of three photos taken with a 105 mm telephoto lens)
   - For each painted or bas-relief decorative element (one photo taken with a 105 mm telephoto lens).

7. This system consists of an optical mirror positioned opposite a camera with a macro lens. The camera is pointed at the middle of the mirror in which the entire scene is reflected (360 degrees horizontally and 105 degrees vertically). Using a software program, the source image is then deformed to produce an equi-rectangular image showing the entire scene represented on the horizontal axis. To ensure that we know which building is the center of attention in a panoramic photograph, the camera is always pointed orthogonally at that building's facade. Thus, the facade of the building in question will be at the center of the photograph. The technique is a very flexible one. We were able to mount the camera and the mirror on a tripod 2.5 m off the ground, which enabled us to remain below the photographic field. Connected to a GPS system, the camera (a Nikon D1X) records its geographical coordinates in a specific field of meta-data (EXIF).
8. The logic underlying photographic documentation is always the same, the only differences being the number of photographs taken and the lenses used. All the photos were taken from the same distance away from the building being photographed. The second image in a block of three photos, or the third in a block of five, was always taken from a position perpendicular to the facade.
9. This process enables us to produce an orthophotograph of decorative elements. We are able to automatically extract the meta-data stored in the relevant files. Each image is accompanied by information including the time and date on which it was taken, the type of camera, the type of lens used, etc.
10. For example, we can search the database to find out which materials were used in a specific construction element or to isolate the different kinds of arcades used in loggias.
11. The system's navigation interface, which can be accessed online, is divided into three parts. The first contains a map of Kashgar indicating the buildings for which we have entered data. This part of the system uses a free SVG file viewer—Adobe SVG Plug-In—which can stock a two-dimensional representation by vector. Various attributes of the geometrical entities can be displayed and different types of interactions (navigation, clicks, etc.) can be set up. All the icons on the map are Javascript-enabled. Clicking on a building icon sends an SQL request to

the database. The request contains the building's identification. The database replies by supplying all the data relative to the building selected and sending them to a PHP page located to the right of the map. This page displays the database response in three parts, corresponding to the three blocks of our conceptual model (information, typology, ressources). The typology block has an icon for each type. The resource block displays all the photographs and miniatures associated with a particular building. Users can enlarge photos by clicking on them. Data are entered in three stages. First, we enter general information about the building. We then select photographs of that buiding stored on the local computer. These photographs are used in the last stage of the process: the description of a specific typology. Referring to photographs of the various parts of the building, users can fill in a form based on the description of the building. For each descriptor, users can choose a type from a list or add a new one to the database. This new type will appear in the file of the next building description entered. In the last stage, an interface (which is currently under development) will make it possible to locate the building on the map of the city. However, this is only a provisional solution, because our aim is to develop an application that will use the GPS coordinates stored in the database to automatically locate specific buildings.

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Chapter 12
The Taklimakan Oases: An Environmental Evolution Shown Through Geoarchaeology

Corinne Debaine-Francfort, Françoise Debaine, and Abduressul Idriss

Abstract Amid the ocean of sand that is the Taklimakan Desert in China's Xinjiang province, evidence of human habitation has revealed a rich pastoral and agricultural history along dried-up waterways through which the Keriya River once coursed. The various states of the river, which had connected the north and south oases of the desert but now disappears into the dunes, are visible on satellite images. By confirming the hypothesis of the existence of ancient agricultural settlements on deltas—nowadays totally dry—of this river, research has clarified settlement patterns over the long term by placing them in the evolution of their environment under the influence of natural or anthropic factors. From the current bed of the Keriya River to its fossil courses, several years of pluridisciplinary studies revealed an evolution of the successive deltas of the Keriya River in at least three periods: current, antiquity (third and fourth centuries AD), and protohistory (c. 2,500–1,000 BC: Bronze and Iron ages). These successive deltas correspond to various stages of desertification. In each of them, an oasis and a vast settlement zone are centered on a main village. Studying these settlements and comparing them with those of Central Asia provides an inventory of the interactions between man, water, and the environment and illuminates constants and variables of change.

Keywords Desertification · Geoarchaeology · Irrigation · Keriya (Xinjiang, China) · Settlement pattern

12.1 Keriya: A Valley "at the End of the World"

The jagged and weathered wooden beams of a dwelling jut out of the shifting sand dunes like spikes, vestiges of a community that once lived in the Keriya River valley before the desert claimed the land. With waves of barren dunes standing as tall as 100 m, it is difficult to imagine that humans ever lived and farmed in this area, the

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G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
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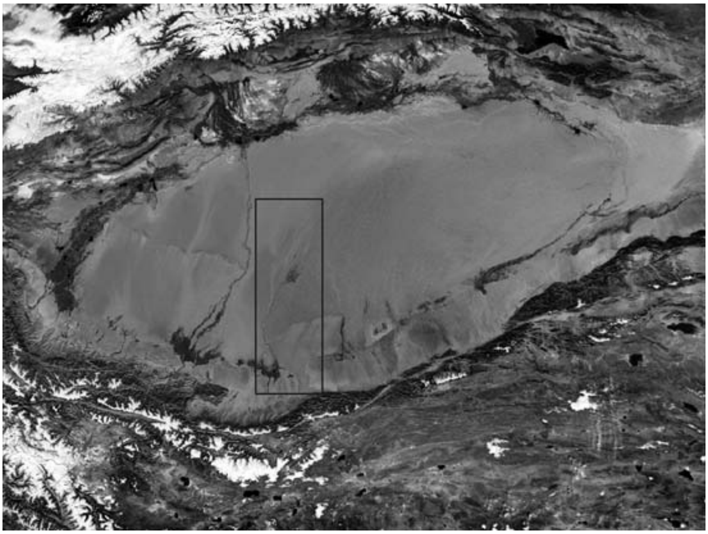

Fig. 12.1 Radar image of the Tarim Basin. In the center, the Taklimakan Desert surrounded to the north by the Tian Shan Mountains and in the south by the Kunlun Mountains. In the *box*, the Keriya valley

heart of the Taklimakan Desert, where camel caravans remain the only means of transport (Figs. 12.1 and 12.3). Indeed, according to Claremont Perceval Skrine, Consul General from 1922 to 1924 in Kashgar, a city bordering the Taklimakan, "In Keriya, there is a feeling of being at the end of the world." Yet archaeological and geological evidence discovered in the region reveals a rich history of human habitation and irrigation, providing a better understanding about the relationships between societies, water, and the environment over millennia in this remote part of the globe[1] (see Chapters 1–4 and 9).

The Keriya River lies in the Xinjiang region of northwest China, an area at the crossroads of great empires (China, India, and Persia) and long traversed by nomads, Silk Road travelers, and sheep and goat herders. Some of those who traveled in this area followed the Keriya River's "green corridor" across the Taklimakan Desert in the Khotan region of southern Xinjiang. Fed by snowmelt from glaciers in the Kunlun Mountains, the river flows to the north (Fig. 12.2). This lifeline once provided a vital communications channel between the north and south oases of the Tarim Basin, an endorheic basin that is home to the Taklimakan Desert. At the end of the last glaciations, about 15,000 years ago, the river coursed across the Taklimakan, between the Kunlun range to the south and the Tian Shan mountain range to the north, and its floodwaters reached the Tarim River until c. 4,000 BC[2] (Fig. 12.3).

After that, due to a reduction in flow, the waters—winding through sand dunes—no longer reached the Tarim, forming an endorheic delta. As the centuries went by, this delta crept from the northwest to the southeast, driven by a slow tectonic shift

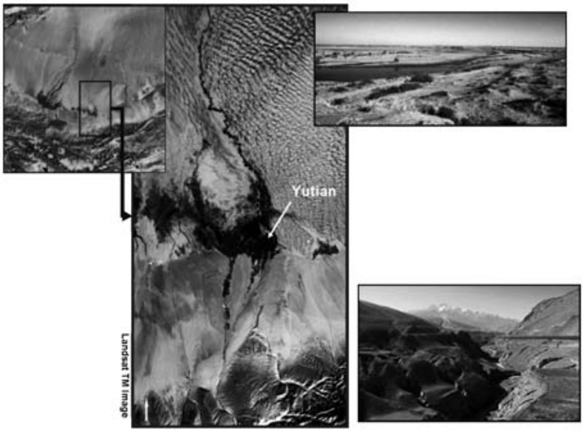

Fig. 12.2 Landsat TM (thematic mapper) image of the valley of the Keriya from its source in the Kunlun Mountains (photo, *lower right*) to its endorheic delta, passing by the Yutian oasis, county seat of the north piedmont of the Kunlun. Photo, *upper right*: middle reaches of the river. © Sino-French Archaeological Mission in Xinjiang (MAFCX)

in the Pamir region. The remains of several successive fossil stages of the river lie to the west and north of the current waterway in a zone now completely claimed by desert. The oldest stages are the furthest to the northwest and are easily identifiable on satellite images (Fig. 12.4).

The first archaeological discoveries—made at the end of the nineteenth century—dated from historic times. But up until the 1980s, the history of the region before the Silk Road (before the first centuries AD) was almost unknown. Thus, the archaeological map of the Keriya River was limited then to two sites, Karadong and Majanlik, dating from the Han-Jin period (c. third century AD) (see Hedin 1904; Stein 1907, 1921; He and Zhang 1990; Wu and Huang 1991).

The exploration of the Keriya by a Sino-French team between 1991 and 2005 was based on the hypothesis that ancient agricultural peoples should have settled along these now-dry branches of the interior deltas, diverting water from the river and digging irrigation canals to create arable lands as early as protohistoric times. An analysis of the paleochannels and the present river course, combined with an analysis of archaeological remains, has confirmed the team's hypothesis. Using the present course of the river as a zero point and receding in time, ancient riverbeds and deltas have been surveyed, and 600 points have been added to the map (Fig. 12.5).

For the time being, the evolution of the population in the successive Keriya deltas can be broken into at least three periods[3]: present day (at least from the 1850s: delta of Daheyan), ancient (the Han-Jin period, third and fourth centuries AD: delta of Karadong), and protohistoric, with at least two successive periods: the Iron Age (first millennium BC: delta of Djoumboulak Koum), and the Bronze Age (c. 2,500–1,000 BC: site 240).[4]

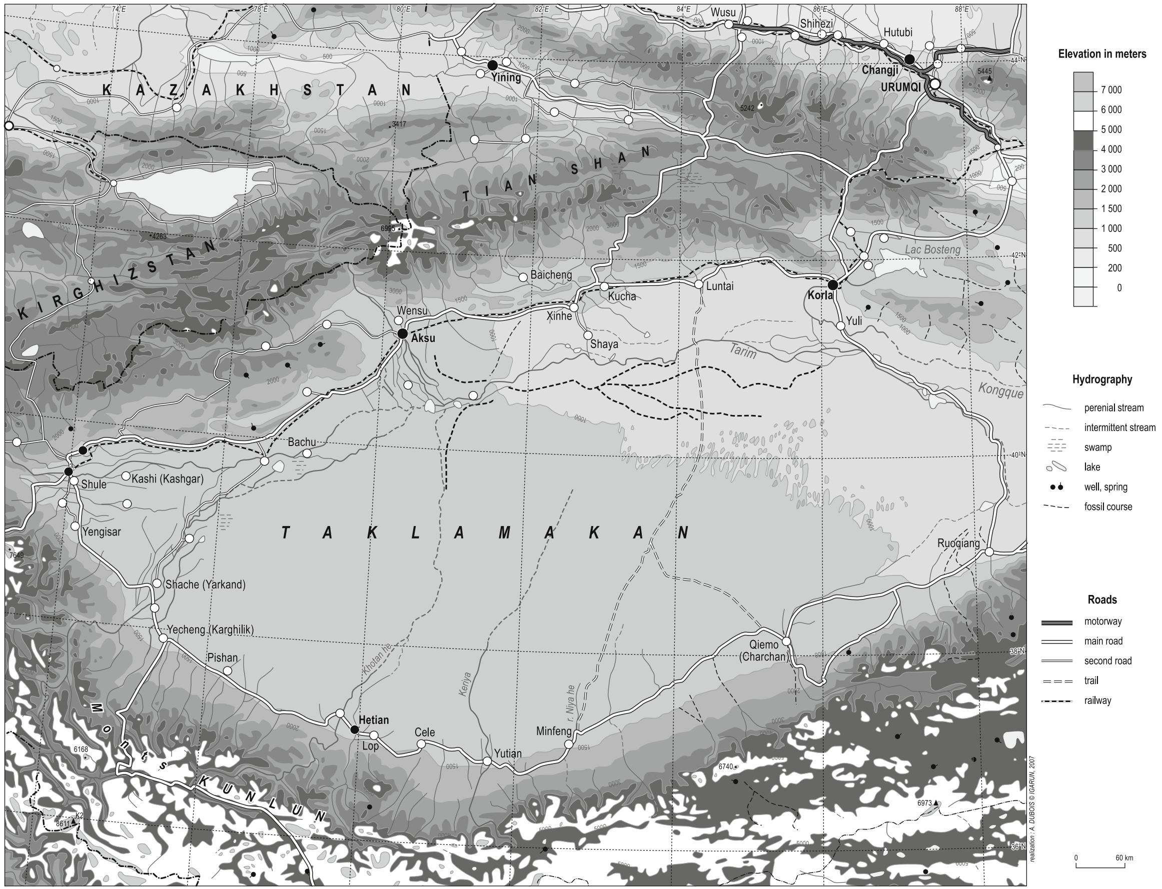

Fig. 12.3 The Xinjiang Uygur Autonomous Region. In the ellipse, the Keriya valley, which in the past linked the Khotan (Hetian) –Yutian oasis in the south to that of Kucha to the north of the Taklimakan. Map A. Dubois © Igarun, 2007

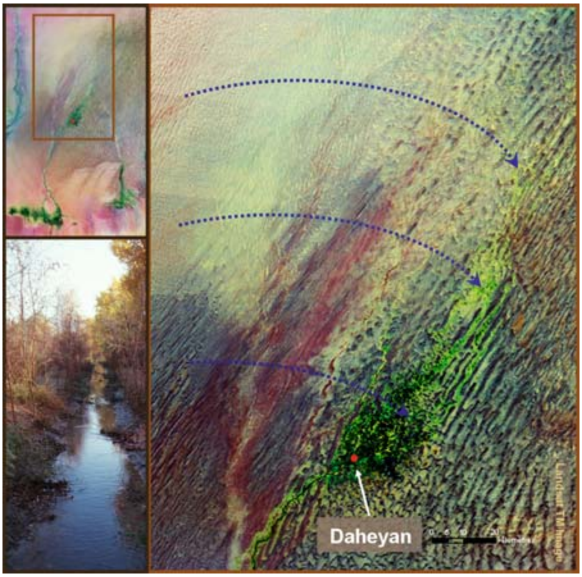

Fig. 12.4 Landsat TM image of the present and ancient deltas of the Keriya, showing a shifting of the river over time from the northwest to the southeast and a regression of its extension. (c) Sino-French Archaeological Mission in Xinjiang (MAFCX). © Sino-French Archaeological Mission in Xinjiang (MAFCX)

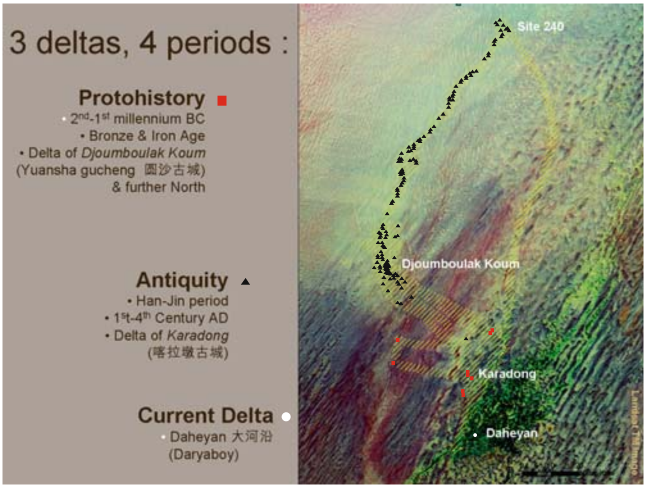

Fig. 12.5 Itinerary of the explorations of the Sino-French team (hatchings): the present Keriya delta (Daheyan); the ancient delta and its capital, Karadong, the oasis of which was occupied at the beginning of our era (*triangles*); and the protohistoric delta (*squares*) occupied at the latest from 2,000–1,000 BC (site of Djoumboulak Koum, Iron Age and site 240, Bronze Age). © Sino-French Archaeological Mission in Xinjiang (MAFCX)

12.2 Daheyan: The Present Keriya and Delta

The current Keriya can be seen as a laboratory for understanding the phenomenon of aridification and interactions between man and the environment (Fig. 12.6). Only in the upper reaches does the water supply remain relatively constant. The river waters

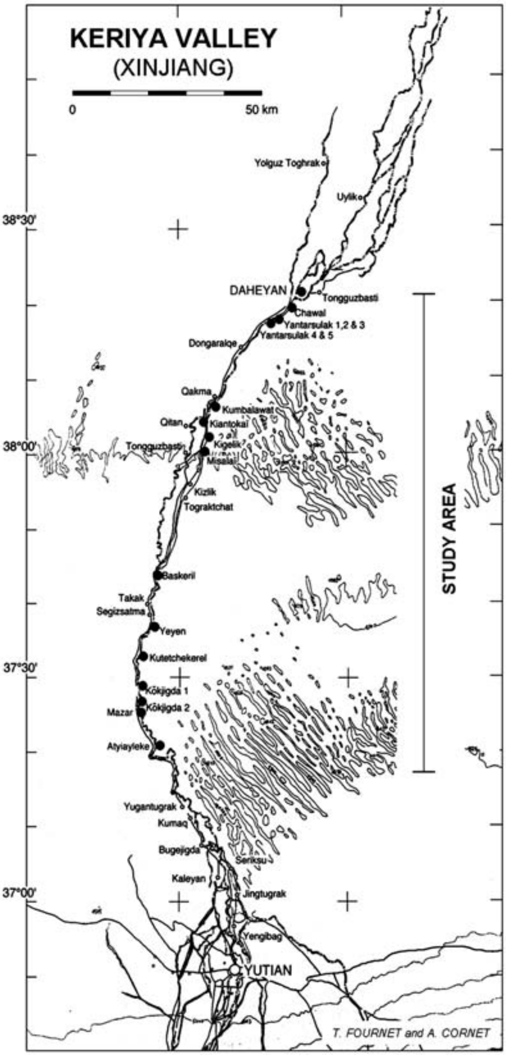

Fig. 12.6 Map of the present course of the Keriya from Yutian on the piedmont to Daheyan in the delta (Fournet and Cornet). *Dots* correspond to the main groups of dwellings that border the right bank. © Sino-French Archaeological Mission in Xinjiang (MAFCX)

ceased to flow to the delta in the late 1980s, fading into the sands of the Taklimakan. Due to the extension of farmland and irrigation upstream in the district of Yutian, the flow of the river in the desert has decreased, starving the downstream riparian poplar forest of water. Despite the constraints, the political will to develop south Xinjiang has boosted the population in the current delta from 864 inhabitants in 1988 to 1,296 a decade later.

Life is concentrated near the water, in the meadows and the riparian forest (tugaï), and on river bank forests where reeds (*Phragmites communis*), poplars (*Populus diversifolia*), and particularly drought-resistant tamarisk (*Tamarix taklimakanensis*, T. *acentoides*) grow. The middle reaches of the river make up a semi-desert

Fig. 12.7 Forest along the Keriya in its middle reaches. The vegetation (reeds, tamarisks, poplars) is characteristic of the tugaï. The tamarisk and poplar mounds (*lower* photo) are indications of desertification. © Sino-French Archaeological Mission in Xinjiang (MAFCX)

zone where reed and salt swamps alternate with salt lands, dunes, poplars, and tamarisks that are characteristic of the tugaï (Fig. 12.7). This area offers little means of subsistence, and houses are spread far apart.

Only the delta can support a larger community. The location of the village of Daheyan (Daryaboy or Darya-boyi in Uygur) corresponds to the mouth of the delta, a strategic point for administrative and commercial control of the valley. Although the location of Daheyan is favorable to the construction of canals from one branch of the river to another, agriculture is not practiced,[5] and the inhabitants note that the waters have receded while the desert has advanced. While the installation of irrigation canals permitting secondary agriculture worked in the ancient and protohistoric periods, the practice is no longer successful because of the irregular flow and poor water quality. However, with the help of retention dams, the villagers distribute the water so that it flows down the various branches of the delta to encourage the growth of poplars, the leaves of which nourish livestock. In these conditions, animal grazing is vital to the economy in the valley and doesn't adversely affect the environment. Each household possesses at least 15 to 150 goats and sheep, sometimes a donkey or camels and, rarely, a horse (Fig. 12.8).

A study by T. Fournet and A. Cornet (see Debaine-Francfort and Idriss 2001) has helped define the basic settlement principle: proximity to the river and the trail that links Daheyan to Yutian, the county seat 200 km south, on the fringe of the desert.

Fig. 12.8 Flock of goats and sheep grazing on the banks of the Keriya. © Sino-French Archaeological Mission in Xinjiang (MAFCX)

This is why the rural space is structured linearly. Indeed, everything vital comes from the river and the trail (Fig. 12.9).

Outside of the county seat, settlements are scattered in the delta and households are separated by a distance of 2 to 30 km. The government allots a fixed parcel of territory to each family that uses its section of the valley (often more than 20 linear km) for grazing. This practice allows flocks and herds to change pastures regularly when vegetation is sparse. Raising goats and sheep also influences the structure of

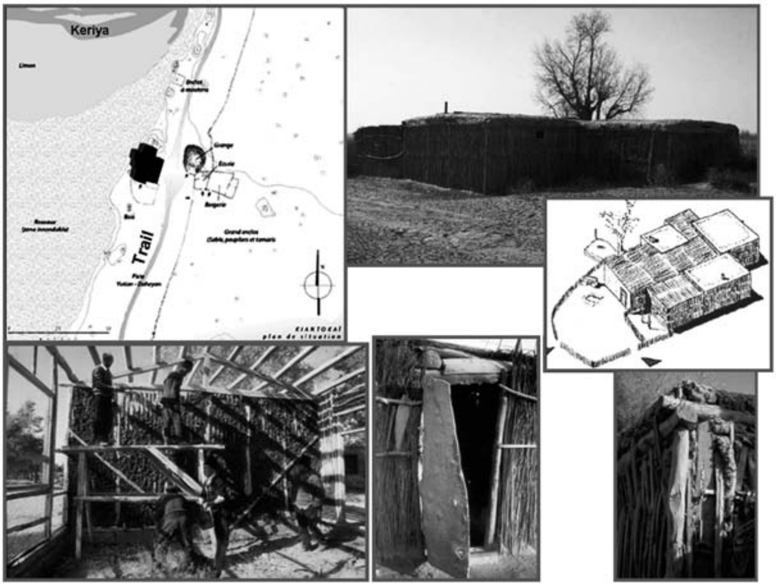

Fig. 12.9 The house of Kiantokaï ("Big Bend") is located on the banks of the Keriya, in the hollow of a meander of the river, about 50 km upstream from Daheyan (Layout Fournet and Cornet). Proximity to the Daheyan–Yutian trail and the presence of a ford make it a highly prized meeting place for the inhabitants of the middle reaches. Like that of the other houses of the valley, the structure is of wood. © Sino-French Archaeological Mission in Xinjiang (MAFCX)

Fig. 12.10 Poplar leaves and branches serving as forage for the animals are stored in enclosures or on special wooden structures (*upper* photo). Each dwelling possesses animal enclosures (*lower* photo). © Sino-French Archaeological Mission in Xinjiang (MAFCX)

the inhabitants' dwellings, which always include an enclosure for the flocks and forage (Fig. 12.10).

Water, consumed by humans and animals, must be drawn daily. The river is a 2- to 15-minute walk from most households; therefore, the possibility of drawing from it directly or possessing a well represents a sine qua non condition for any settlement (Fig. 12.11). The riverbank vegetation provides pasture for the livestock and construction material for the houses, which are built of poplar, tamarisk, reeds, alluvium, and sand.

Finally, the subsistence products not immediately available come by the trail, the only link between Yutian and the delta. Valley inhabitants travel to Yutian to buy vegetables, cereals, and manufactured products. While there, they sell meat, skins, goat hair and wool, fox furs, and tubers of broomrape (*Cistanche salsa*) sought for their medicinal properties.

12.3 Karadong: The Ancient Delta

The capital of the ancient delta, Karadong (Kaladun or Haladun, in Chinese) lies 20 km from Daheyan and was discovered in 1898 by the Swedish geographer and explorer Sven Hedin (Hedin 1904) (Fig. 12.12). Excavated very briefly by Sir Aurel

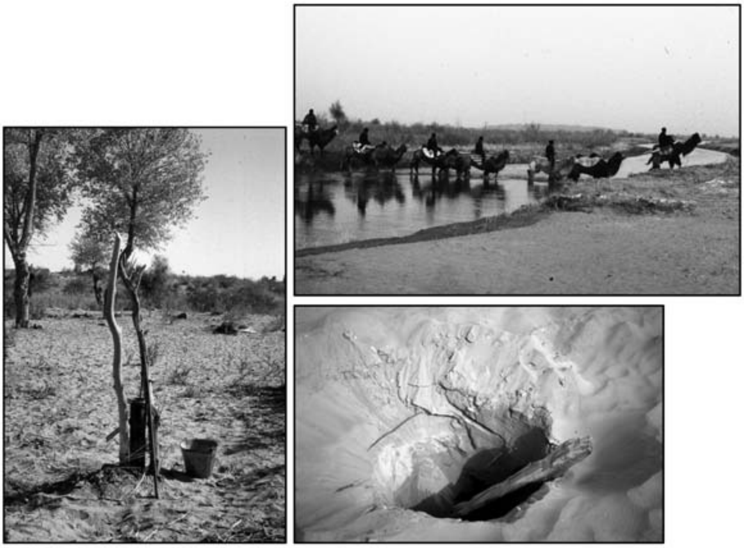

Fig. 12.11 *Upper right*, crossing the Keriya near the delta. *Bottom right*, *left*: wells dug near the dwellings of the middle reaches. © Sino-French Archaeological Mission in Xinjiang (MAFCX)

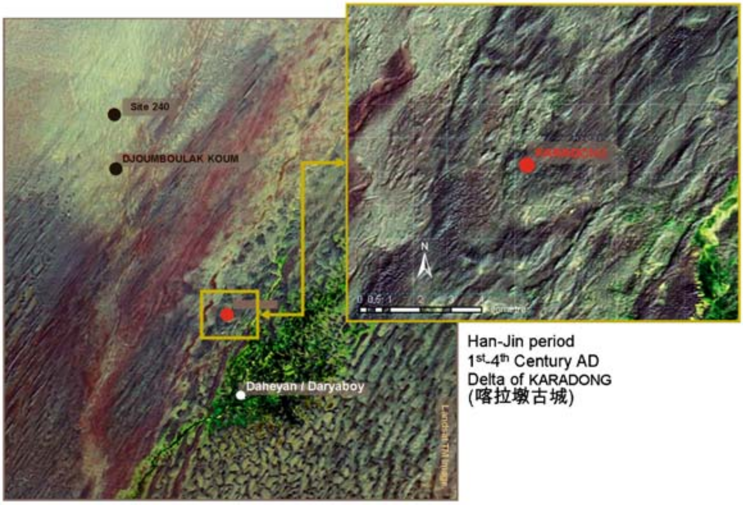

Fig. 12.12 Landsat TM image of the Keriya deltas. Karadong, capital of the delta in antiquity. © Sino-French Archaeological Mission in Xinjiang (MAFCX)

Stein (Stein 1907, 1921), it was the only important site known in the valley as late as 1991.[6]

Three campaigns of excavation in situ have allowed for new discoveries. Once a caravan stop and a checkpoint on the road to Kucha, north of the desert, the site was abandoned toward the end of the third century. Engulfed by sand, it bears

Fig. 12.13 Tamarisk and poplar mounds in south Karadong. These formations are indications of severe desertification. © Sino-French Archaeological Mission in Xinjiang (MAFCX)

the remains of a farming community, with a small fort; about 30 farm, public, and religious buildings; roughly 20 dwellings; craft activity areas; and irrigation channels. The ruins are scattered across a strip approximately 3 by 1.7 km and shed light on the workings of the oasis and its relationship with neighboring regions.

The tamarisk and poplars, still visible among the dunes, are the vestigial vegetation of the paleochannels of the Keriya, the alluvial terraces of which are partially preserved. These trees rise on mounds created over the course of time by the accumulation of generations of dead leaves and the fragments of branches that have fallen on the ground (Fig. 12.13). The development of these mounds is an indication of severe local desertification.

The inhabitants' wooden houses, like those of the current delta of the Keriya River, were built as small domains along shady canals and included living areas and outbuildings for the animals. Unlike present day, however, these dwellings were surrounded by gardens, orchards of blackberry bushes and fruit trees, vines, and cultivated, irrigated terraces. That lush vegetation exists today in oases at the desert's edge or in the piedmont but is no longer found in the middle reaches of the river or in the Keriya delta.

Irrigation enabled the inhabitants of Karadong to exploit their environment, a fragile equilibrium that was more suited to hunting and animal husbandry. Traces of a rather complete irrigation network stretch more than 1.8 km in the southern part of the site where two water inlets were also identified. Topographical and stratigraphical evidence suggests that inhabitants repeatedly had rebuilt certain branches of irrigation channels during successive repairs. These canals, rectilinear or winding, with vertical or oblique sides of raw clay, globally flow from the north to the south. Lined with poplars and blackberry bushes, they measure 50–90 cm wide and 20–25 cm deep (Fig. 12.14).

Other canals are equally preserved in the northern part of the site, particularly to the east of the fort where remains of plots of land have been identified (Fig. 12.15).

Fig. 12.14 Karadong, south zone. Rectilinear canal. © MAFCX

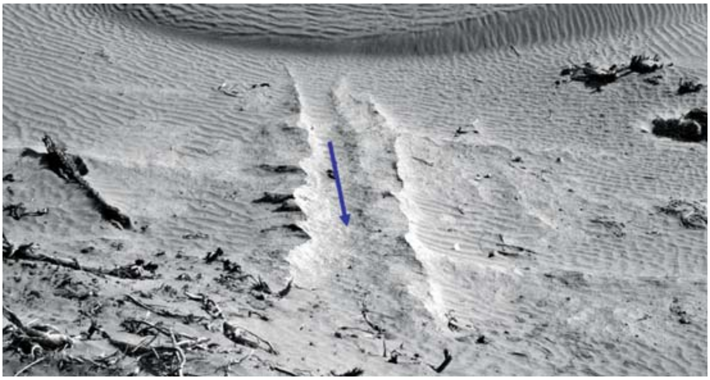

Fig. 12.15 Karadong, north zone. Remains of irrigated parcels. © MAFCX

A circular water tank with a diameter of about 30 m was also discovered near a dwelling[7] (Fig. 12.16).

A scanning electron microscope[8] used to examine sediments from Karadong revealed that, at the time of human habitation, environmental conditions were already markedly arid, and that the site sat near the limits of the annual floodwaters. Dunes were present in the immediate vicinity of the site and fine sediments (sand and alluvium) were deposited by the river at irregular flood levels. A probable contraction of these floods would have brought about the migration of the inhabitants and the later amplification of aeolian processes (untilled fields, etc.). However, the floods still reached Karadong after the site was abandoned, and evidence suggests

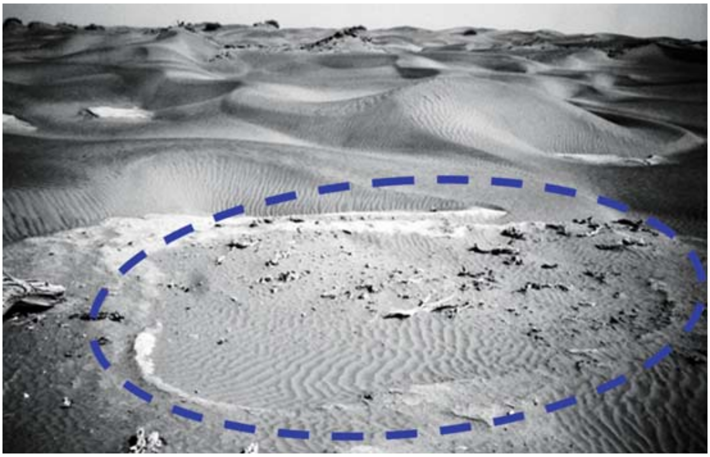

Fig. 12.16 Karadong. Circular water tank. © MAFCX

that desertification of the oasis resulted from a progressive phenomenon and not a sudden desiccation. Conditions were no longer present for the permanent occupation of the site, but enough water and vegetation remained so that the abandoned parts of the village could have served as pasture before they were claimed by desert.

Outside Karadong itself, the discovery of other installations, although modest, provides evidence that a population was established in the whole of this ancient Keriya delta between approximately the second and fourth centuries AD.[9]

12.4 Djoumboulak Koum: The Protohistoric Delta

The discovery of Djoumboulak Koum, 41 km from Karadong and further in the desert, provided proof that this remote delta, older than the delta of Karadong, had supported a farming population founded on artificial irrigation in ancient times. Dating back to the Iron Age (middle of the first millennium BC), the city of Djoumboulak Koum provided the first evidence of a population before the Han period (third century BC to third century AD). Exploration around the city resulted in a better understanding of the culture as well as the temporal and spatial span of the population found to have lived in Djoumboulak Koum, and turned up evidence of the existence of an even older population (Fig. 12.17).

12.4.1 Djoumboulak Koum: a Fortified Settlement of the Iron Age

Djoumboulak Koum (Yuansha gucheng, in Chinese) was an oasis capital in the protohistoric delta of the Keriya during the middle of the first millennium BC. The site itself is barely visible in the ocean of sand dunes surrounding it. However, better than a site, this is a complete ensemble: a fortified city of 10 hectares (ha), with its

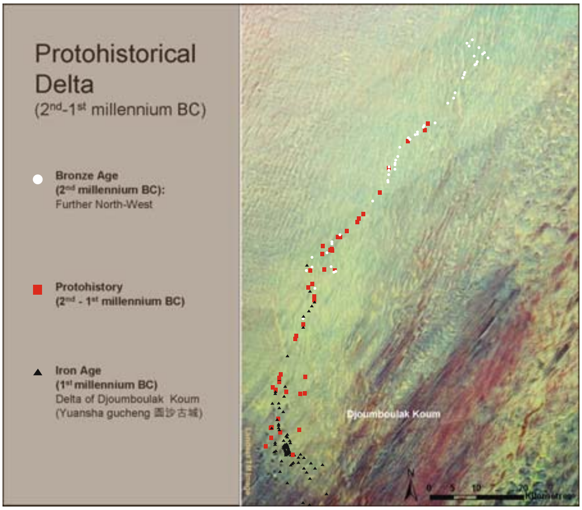

Fig. 12.17 Exploration of the protohistoric delta of the Keriya (*squares*) (Landsat TM Image) has revealed evidence of several phases of population attributable to the second and first millenniums BC. Djoumboulak Koum was the capital of the oasis occupied during the Iron Age (*triangles*). Traces of more ancient populations can be found to the north. © Sino-French Archaeological Mission in Xinjiang (MAFCX)

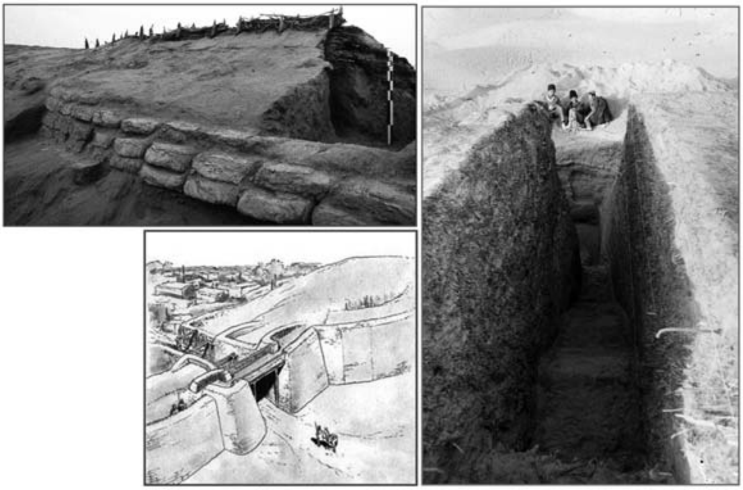

Fig. 12.18 Djoumboulak Koum. *Upper left*, part of a rampart in earth reinforced with branches and unbaked bricks. Underneath, reconstruction of the south gate. At *right*, a trial trench near the port presents a stratigraphy of more than 7 m deep of organic material, preserved by the dry climate. © MAFCX

cemeteries outside its walls. Located in an irrigated environment, the site was part of a densely populated zone that covered an area of at least 20 by 15 km.

Unlike Karadong, Djoumboulak Koum was a fortified city; building and developing it must have demanded considerable resources. The rampart, reworked several times, is massive and stretches more than 720 m. Near the south gate is a stratigraphy, rare in Xinjiang, of more than 7 m of very well preserved organic remains (Fig. 12.18), which provided previously unknown information concerning animal husbandry and agricultural practices. Intramuros, vast wooden-structured dwellings, including outbuildings for the animals and small silos in raw clay, were excavated. Here, as in other deltas of the Keriya River during historical periods and today, poplar wood is omnipresent in the frames of the houses, and poplar leaves served as forage for the goats and sheep. Poplars, tamarisks, and rushes—the principal materials found locally—comprise the common denominator of the cultures of the region from protohistory to today.

12.4.1.1 Exploitation of the Environment and the Way of Life

Although they exploited the resources of their nearest environment, the inhabitants were far from isolated, and their city was very different from the Daheyan of today. The archaeological material reveals that the residents had connections with areas of the neighboring piedmonts to the north and south,[10] and, before the Silk Road, with regions farther away, including Chinese mainland, the Indo-Pakistani subcontinent, and Central Asian oases and steppes. Who, then, were the inhabitants of this city, buried outside its walls? They likely were farmer-shepherds, weavers, and craft workers who used irrigation and grew grain well before the Han and the arrival of Chinese settlers from the second to first centuries BC.

The study of S. Lepetz (see Debaine-Francfort and Idriss 2001) shows that animals had an important role in the economy (Fig. 12.19). Goats, sheep, oxen,[11] camels, horses, dogs, and roosters were domesticated. Cut marks found on bones indicate that animals were slaughtered, and the range of animal ages indicates the herds were managed to provide meat and wool. The remains of wild animals (deer, rabbit, and wild pig) are rare but point to the existence of a developed riparian forest.

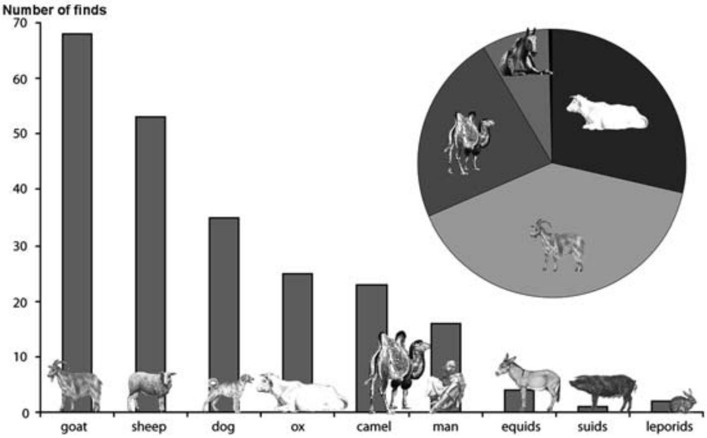

Fig. 12.19 Djoumboulak Koum. Animal species recognized from collected fur (diagram); relative proportion of domesticated animal species (circular diagram) (S. Lepetz). © MAFCX

An archaeobotanic study (C. Newton; see Debaine-Francfort and Idriss) provides information on the environment of the site and agricultural practices. It allows reconstruction of areas of natural vegetation and artificial irrigation. The species of wood identified were poplar (*Populus* sp. *Populus euphratica*), tamarisk (*Tamarix* sp.), sallow-thorn (*Hippophae rhamnoides*), oleaster (*Elaeagnus angustifolia*), and mulberry tree (*Morus* sp.). In addition, reeds (*Phragmites communis*) and other herbaceous plants (*Poaceae*, *Zygophyllaceae*, *Chenopodiaceae*) are characteristic of the tugaï. This riparian forest seems to have been largely exploited as a source of raw material (wood, forage and fruit, and dyeing products) and as hunting grounds. The domestic plants vary little: common millet (*Panicum miliaceum*), six-row hulless barley (*Hordeum vulgare* var. *nudum*), and soft wheat (*Triticum aestivum/durum)*. While the present delta cannot support the growth of cereal crops, the protohistoric culture in situ has revealed abundant remains from harvests and grain preparation. If millet can be cultivated along the riverbanks during the summer floods, wheat cannot be grown without irrigation.

12.4.1.2 Irrigation Network

Traces of an irrigation network—the oldest of its kind known to exist in Xinjiang—cover several kilometers. The network also provides new information about the region's inhabitants—often envisaged only as pastoral nomads—during the first millennium BC and gives Xinjiang its place in the development of agricultural societies of Central Asia. As in Karadong, irrigation consisted of units of small canals, about 50–150 cm wide, that joined together in a configuration to allow clan-type societal groups to irrigate large territories without the need of a state-controlled system.

To the north of Djoumboulak Koum, the network has several visible courses and a level of terraces with reeds of the same period as the canals (Fig. 12.20). A section

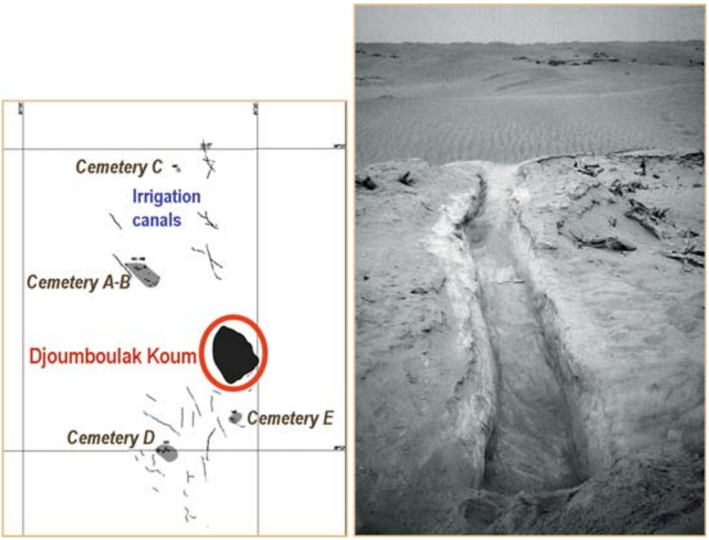

Fig. 12.20 Djoumboulak Koum. North network canal. © MAFCX

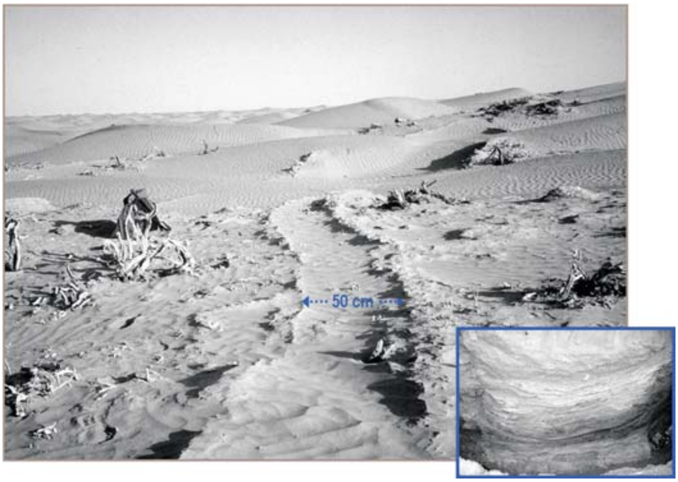

Fig. 12.21 Djoumboulak Koum. Canal (50 cm wide) and section. North network. © MAFCX

of a canal is 50 cm wide and 20–25 cm deep, with more than 30 cm of foliated layers of sand-alluvium, indicating a lasting use of the canal. The network also shows evidence that canals were repeatedly cleaned out. Some of them had been discarded; others were rebuilt (Fig. 12.21).

To the south, a water supply point for a distribution network is identifiable on a terrace. The width of the north–south main canal measures 140 cm. It cuts east to west across an older course measuring 40 cm wide, and divides itself into two secondary canals with a width of 60–70 cm.

12.4.2 The Oasis of Djoumboulak Koum

Occupation of the protohistoric delta was not limited to this large site. Northwest of Djoumboulak Koum, archeological evidence discovered in 94 places over more than 40 km along the fossil river arms bears witness to continued occupation of this zone; sections of the canals and the wood cuttings that remain show that it was carefully exploited (Fig. 12.22).

The nature and the density of the archeological finds vary considerably according to the state of conservation of the terraces, the courses, and the vegetation along them. One area may contain only potsherds or scattered fragments of millstones, metal objects, slag, glass beads, and animal remains. Another area might have the remains of hearths, manure, prints of human feet and animals on the alluvium of the terraces, and again, evidence of construction, graves, or cemeteries. The most important discoveries (site 107) are those of a village found 14 km from Djoumboulak Koum. Greatly eroded, this site has revealed abundant material, silo bottoms and hearths, and a section of an enclosure wall; remains of dwelling structures have not been found.

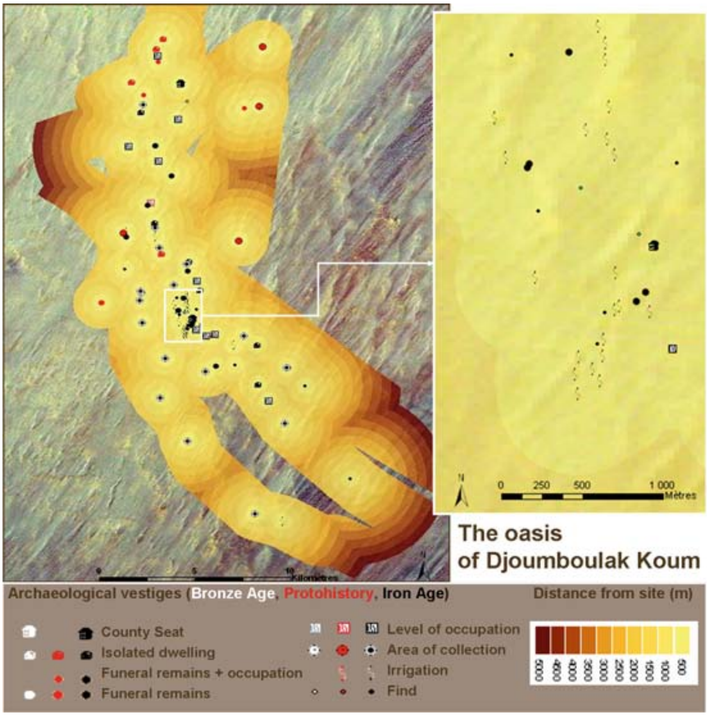

Fig. 12.22 Occupation of the protohistoric Keriya delta. The oasis of Djoumboulak Koum. © MAFCX

12.4.3 Before Djoumboulak Koum: The Bronze Age Recaptured

In a general way, the more one progresses toward the north, the more the water courses are full of sand, the erosion is extensive, and artifacts and remains are less well preserved, even if certain branches of the river are still apparent. Here and there, however, traces of ancient irrigation and archaeological remains testify to human occupation.

The first signs of a cultural change appear around latitude 39°, about 28 km north of Djoumboulak Koum. They manifest themselves in the appearance of red ceramics of a particular type that are difficult to date because they were found out of their stratigraphic context and for the moment do not belong to any known cultural group. About 15 km further north and on different sites, remains similar to those found in Djoumboulak Koum coexist with earlier remains. More to the north (about 80 km northwest of Djoumboulak Koum), vestiges of the Djoumboulak Koum-type disappear, replaced by a more ancient archaeological culture that can be attached to the Late Bronze Age[12] (see Fig. 12.17).

These remains (112 spots) include evidence of constructions like sheepfolds and levels of organic material that correspond to the spread-out houses and properties on the banks of the river with, as in the Keriya of today, a principal dwelling and its outbuildings surrounded by exploited land. The remains of a more important site (240) with three groups of some kind of building—perhaps a house—and rich in ground finds were found at the end of 2005.[13] These are, for the moment, traces of the most ancient phase of human habitation known in this region. They bring new confirmation that the population of the Keriya valley is linked to the evolution of the environment over millennia.

12.5 An Unbalanced Equilibrium

This survey of the different occupations of the Keriya deltas from the Bronze Age to the present helps define the permanent features of the settlement patterns and mode of exploitation of the land over a period of approximately 4,000 years. The factors of continuity dominate because of the strong constraints imposed by the environment. All of the Keriya delta communities have been characterized by an oasis and a populated area centered on a city or main town. This is true of Daheyan, Karadong, Djoumboulak Koum, and Bronze Age site 240. The settlement pattern is linear and follows that of the branches of the delta. The hierarchy of the delta's internal network determines the typology of the irrigation and that of the sites (capitals situated within the system, secondary sites on the margins, etc.). Whatever the period considered, the environment in which the settlement areas exist is unstable over the long term, as well as at the scale of a year. Neither the structure of the dwellings nor the materials and techniques used to build them has evolved greatly. Similarly, the exploitation of the riparian forest, the pastoralism, the agricultural practices, and the means of irrigation remain remarkably unchanged.

However, it is at the level of the agricultural practices that the most notable changes appear: the regression of the river's courses and the deltas as well as the lessened competence of the river have progressively reduced water resources, diminished the size of the oases, and led to an impoverished biodiversity. The present delta does not allow for growing grains. The number of species of domesticated animals such as the ox has fallen. The progressive rupture of an equilibrium, fragile but maintained for centuries, seems to have greatly accelerated during the last 50 years. Today, one has to look at the piedmont zones and the oases at the fringes of the desert to find a situation comparable to that which has been observed for the ancient past and protohistoric times.

Notes

1. This paper is the result of research carried out since 1991 by the Sino-French Archaeological Mission (MAFCX), grouping together a pluridisciplinary team based on cooperation between the French National Center for Scientific Research (CNRS, UMR 7041, the Central Asian team) and the Xinjiang Institute of Archaeology and Cultural Relics (Xinjiang Wenwu Kaogu Yanjiusuo), with the support of the French Ministry of Foreign Affairs and the Chinese National Bureau for Cultural Heritage (Guojia Wenwuju).

2. On the present and past environment of the Keriya, see particularly: Chen, et al., 2003; Coque 1992; Coque and Gentelle 1991; Coque, et al., 1991; Fan 1995; Gentelle 1992, 1995a, b; Gibert, et al., 1995; Jäkel and Zhu 1991; Li and Zhao 1995; Team for scientific exploration of Keriya 1991; Yang 2001; Yang, et al., 2002; Zhou and Zhu 1994; Zu, et al., 2003). On our work in the Keriya, see particularly: Francfort 1993; Debaine-Francfort and Francfort 1993; Debaine-Francfort and Idriss 2001, 2005; Debaine-Francfort, et al., 1994; Idriss and Zhang 1997; Xinjiang Provincial Institute 1998).
3. For each period, the different ways of settlement and land exploitation have been analyzed, first by mapping the archaeological sites in relation to the ancient hydrographic network visible by remote sensing, then by gathering data on the evolution of the agricultural and economic practices of the successive inhabitants.
4. Various samples are being analyzed for dating. Among the first results reaching us, a sample from site 83 has been dated by C14 at 2,624–2,469 BC (Centre de Recherche et de Restauration des Musées de France, [French Museums Center for Research and Restoration] C2RMF, Palais du Louvre, Paris). For the time being, this sample is the most ancient one.
5. Some attempts, in the early 1990s, failed.
6. The first stage of our way back in time, Karadong was not, however, the aim of our research. Occupied at the beginning of our era, it was for us a ‘late’ site; it then became the point of departure of our exploration of the ancient courses of the Keriya.
7. It is the only structure of this type found during all our explorations.
8. By B. Coque and Liu Wensuo.
9. As our objective was the study of the protohistoric delta, we did not try to determine the precise dimensions of this population. This explains the small number of ancient sites on our map.
10. Various stones from Tian Shan and Kunlun mountains, for instance.
11. Our explorations have attested to the presence of oxen, now gone from the delta, all along protohistory.
12. See note 4.
13. This site is about 93 km to the north of Djoumboulak Koum.

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Part III
Management for Sustainability

Chapter 13
How the Predominance of Water Resources Informs Management

Jean Margat

Abstract While a number of different kinds of water resources can coexist in a given country, generally speaking, one type in particular predominates based on hydrographical and hydrogeological conditions. Countries or territories located in arid and semiarid zones can therefore fall into three categories, according to their predominant type of water resources: internal renewable resources, external renewable resources, and nonrenewable resources. The types of predominant water resources and the differences in resulting total water resources have a visible impact in terms of explaining current differences in economic development and geopolitical issues in general. In all cases, development and food security seem to be highly dependent on trade with developed countries located in humid zones. In the long term, differences in variously sustainable sources of supply may have the greatest impact on development.

Keywords Development · Nonrenewable resources · Renewable resources · Scarcity · Virtual water

13.1 Water Resources in Arid and Semiarid Zones

Perhaps it would be useful to start with a truism. Climate is, evidently, the primordial factor in terms of the origin of natural and renewable water resources in a given territory. But the total water resources that a given country is able to rely upon also depends on its location in terms of regional hydrographic structures—which do not generally conform to countries' geopolitical configuration and can determine incoming and outgoing transborder water courses—and on its hydrogeological constitution, which determines subterranean water reserves independently of current climatic conditions. Consequently, a traditional distinction can be drawn between internal and external water resources and renewable and nonrenewable water resources.

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G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
DOI 10.1007/978-90-481-2776-4_13, © Springer Science+Business Media B.V. 2010

Aridity, which is, of course, caused by climatic factors, is the obvious cause of water resources scarcity in territories located in arid and semiarid zones. In addition, two other kinds of water resources exist that are unaffected by climatic conditions but are highly dependent on the variable hydrographical and hydrogeological factors of given territories: external renewable resources and "inherited" nonrenewable resources.

Reciprocally, internal and external resources can be subject to upstream constraints in cases in which water flows across borders and out of the territory. The term "territory" indicates, in this context, certain entities which are or were not internationally recognized, such as the West Bank and Gaza, now controlled by the Palestinian Authority, and Western Sahara.

While in all climatic zones a number of different kinds of water resources can co-exist in a given country, generally speaking, one type in particular predominates. Countries or territories located in arid and semiarid zones can therefore be categorized according to the type of water resources that predominate. Countries thus fall into three different categories: internal renewable (IR) resources, external renewable (ER) resources, and nonrenewable (NR) resources (Fig. 13.1) (Margat 1979, 1985, 1996).

The predominance of one type of resource in a particular country can be gauged by both its territorial extension and its relative importance as a percentage of that country's overall water resources. Nevertheless, in certain cases, territorial predominance does not correspond to predominance in terms of overall water resources. An example of this is Algeria, where, due to the sheer size of the Sahara, nonrenewable resources predominate in terms of extension but not in terms of quantity.

This typology can also be used to elaborate a zoning map of the world's arid and semiarid regions, providing more detail than a mere list of countries and territories. The map in Fig. 13.2, therefore, provides a better description of the diverse

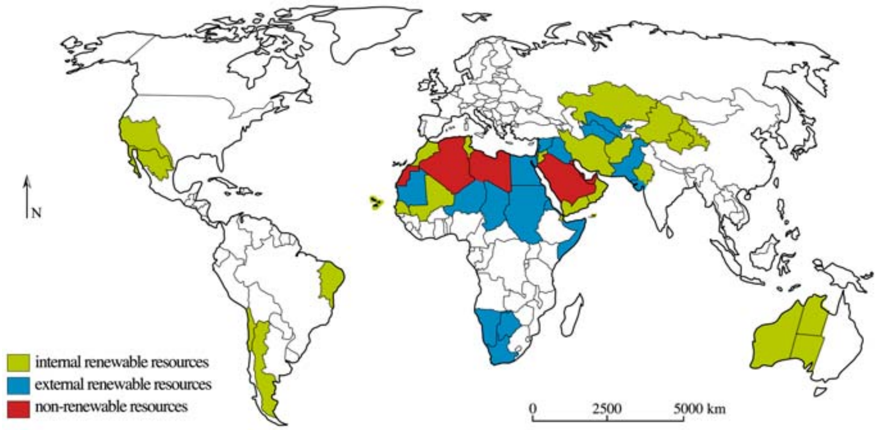

Fig. 13.1 Countries and territories in arid and semiarid zones classified according to predominant water resources

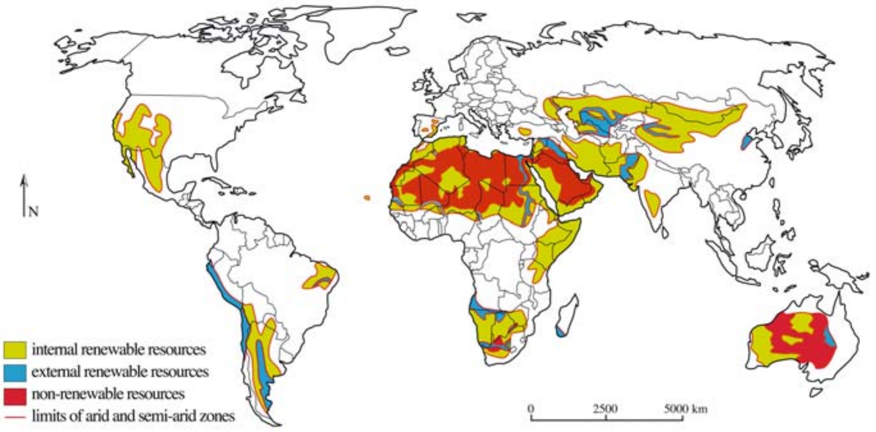

Fig. 13.2 Zoning map of types of predominant water resources in arid and semiarid zones across the world

geography of the three types of predominant resources. This is especially true in geographically extensive countries with pronounced climatic contrasts located only partially in arid and semiarid zones, such as Argentina, Australia, Brazil, China, the United States, India, Mexico, and Russia, which do not appear in Fig. 13.1.

This categorization, which is based on the predominant type of water resource as much as, if not more than, on the degree of rarity of total resources (both per capita and in the absolute sense), necessarily has major consequences in terms of the economics and politics of water in individual countries. This is especially true in developing countries located either totally or mainly in arid or semiarid zones.

It should be recalled that aridity—and the various degrees of aridity—is essentially a climatic concept. The geography of arid and semiarid zones used here was established by UNESCO in the *Map of the World Distribution of Arid Regions* (1977) based on the method developed by P. Meigs. This is the most commonly adopted approach. The countries and territories described as "arid" are located either entirely or for the most part in arid or semiarid zones as defined in the UNESCO map.

13.1.1 Predominant Resources: IR, ER, and NR

The distinctive characteristics of these three types of water resources in the context of arid and semiarid zones are:

- Internal renewable (IR) resources are rare, spread out, and irregular due to annual rainfall rates that are not only generally low (no more than 100–200 mm per year in an arid zone) but also are highly variable chronologically and geographically and substantially lower than the potential annual evaporation. They are affected by large seasonal variations as well as by substantial variations year to year. In

Table 13.1 Estimate of natural renewable water resources (blue water) in the world's arid and semiarid zones. The table compares the total water resources (IR) of each region with the resources of the arid zones of these regions to show the latter's extreme relative weakness

Average flows in km^3 per year

		External resources deriving from humid zones			
AQUASTAT regions	Internal resources in arid and semiarid zones	From the region	From another region or regions	Total in arid or semiarid zones	Total IR resources of each region
North America	168	—	—	168	6,709
Central America	0	—	—	0	787
South America	140	83	—	223	12,380
W. and Central Europe	32	26	—	68	2,181
Eastern Europe	33	305	—	338	4,693
North Africa and the Sahel	62	60	176[a]	298	201
E., W. and Central Africa	13	13	—	26	3,294
Southern Africa	13	47	16[b]	76	455
Africa Total	88	312	—	400	3,950
Middle East	117	102	—	219	491
Central Asia	148	100	5[c]	253	289
South and East Asia	318	264	—	582	11,720
Oceania–Pacific	30	10	—	40	911
World	1,074	1,217	—	2,291	43,764
% of world IRWR	2.45	2.78		5.23	100

[a] From West, Central, or East (Nil)
[b] From Central Africa
[c] From Eastern Europe (Russia)
Source: FAO/AQUASTAT 2003.

drought-affected years, generally occurring every decade, rainfall can be as little as a tenth of the average year. Rainfall also varies in quality; salinity is a frequent problem. Overall, rainfall in arid and semiarid zones accounts for 1,000 km^3 per year, approximately 2.5% of total world natural water resources (Table 13.1). IR resources are exclusively made up of what are now referred to as blue water sources, the unique focus of traditional hydrological measurement (total runoff) derived from water infrastructure and statistics concerning water use.

Nevertheless, while minimal in arid zones, green water sources—useful evaporation–transpiration flows used in rain-fed agriculture—are far from negligible in Central Asia, the Middle-East, Morocco, Iran, and other semiarid zones (see Chapter 7). They should be taken into account in these zones as potential water resources in spite of the difficulties associated with measuring them, and where they can be compared to conventional resources (blue water) while not being confused with them. Internal blue water resources include surface water and subterranean water, which are largely interdependent. Surface flows are inconstant or episodic, ranging from a few millimeters to thousands of cubic meters per square kilometer per "average" year. Efforts to control such flows are obstructed not only by frequent problems affecting hydrographic networks, such as internal drainage and areism, but also by high levels of evaporation (1–2 m per year) that impact reservoirs, which also have to contend with a high risk of silting. For these reasons, a percentage of usable surface water is effectively non-sustainable.

Thanks largely to the surface flows that intermittently replenish them, subterranean aquifers are, in effect, the only permanent resources. But their size and accessibility, which depend on hydrogeological conditions, vary considerably (Zektser and Everet 2004). Furthermore, due to the number of people and industries using the aquifers, they are often over-exploited. Pollution is another issue that has a negative impact on their efficiency as a water resource. Their exploitation can also sometimes be limited by the need to conserve natural sources of the rare areas of permanent surface water used by local populations, but not when water loss is associated with unhelpful evaporation/transpiration typical of sebkhas, or smooth flat plains high in salt. Thus, in arid zones, renewable subterranean water sources are often more accessible than in humid zones, despite the fact that they are rarer.

A good example of a system of exploitation of IR resources is the qanat, which in fact can be considered an artificial spring (see Chapters 5 and 6 and 8–10). Using wells and tunnels to collect and distribute groundwater, qanats are a major feature in the arid zones of the ancient world, particularly Iran, Central Asia, and peri-Saharan Africa. The systems have two important virtues: they consume very little energy and they cannot be over-exploited. However, the use of this system is in decline and is being replaced by pumps, which, while more productive and more easily adapted to meeting specific water needs, are less efficient because they waste more water. Qanats are, in effect, medium-sized, natural, internal resources. Without taking into account the difficulties associated with accessing and exploiting them, most qanats provide, according to figures published in 2000, less than the poverty threshold of 1,000 m^3 per capita per year, and, in 20 countries, less than 500 m^3—the quantity needed to sustain life (Fig. 13.3). Threshold values for the macroscopic indicator "natural water resources per inhabitant" were suggested by M. Falkenmark (1986) for countries in which irrigation is necessary to guarantee food products. "Chronic" water shortage thresholds (1,000 m^3 per year per inhabitant) or "structural," "absolute" shortage thresholds (500 m^3 per year per inhabitant) are average values which correlate closely to the "pressure on resources" indicator (percentage of reserves used), but are less easily applicable to specific conditions and regional

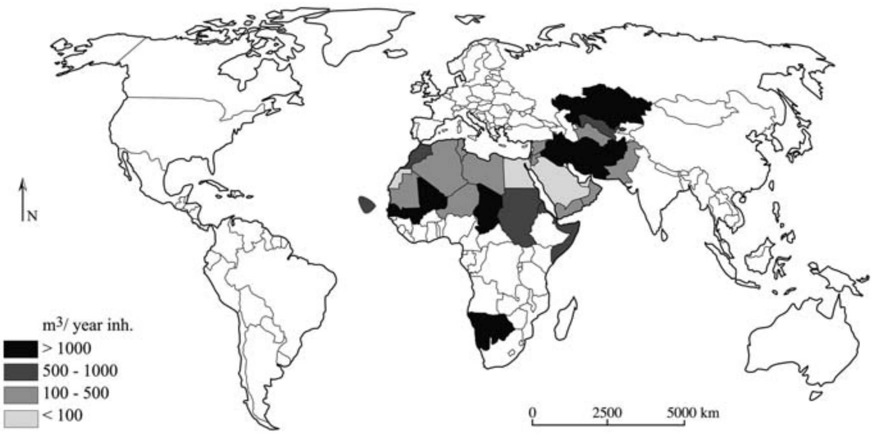

Fig. 13.3 Natural renewable water resources per capita (in terms of 2005 population figures) for countries in arid and semiarid zones
Source: FAO/AQUASTAT, IRWR

variations within individual countries. Strikingly, due to the fact that, in such countries, demographic growth is generally higher than worldwide averages (Clarke and Noin 1998), IR resources per inhabitant decreased more rapidly—by two-thirds—in the second half of the twentieth century than in humid zones, where they were halved. If this trend continues in the twenty-first century, per capita internal resources will be a sixth of what they were in the first half of the twentieth century in arid and semiarid zones, and a quarter of what they were in humid zones (Fig. 13.4).

- External renewable (ER) resources are provided by cross-border or border water courses generally originating in a country, or within a region of the same country, with a more humid climate. These water courses have a variable flow rate but one which is often permanent. These water sources can also take the form of subterranean, cross-border water courses. The best known examples of such sources of river water, which are vital for countries in arid zones, are the Nile (Egypt), the Euphrates and the Tigris (Iraq and Syria), the Amu Darya and the Syr Darya (Uzbekistan and Kazakhstan), and the Indus (Pakistan). Water resources such as these often dwarf their internal alternatives (Table 13.2).

A number of large countries located in arid and semiarid zones are highly dependent on external resources, a phenomenon measured in terms of "dependency ratios" (Table 13.3). Overall, countries and territories in arid and semiarid zones derive about as much water from ER as IR resources, and sometimes a little more: approximately 1,200 km^3 per year. These resources, however, are very unequally distributed (see Table 13.1). ER resources are shared by one or more countries upstream. Accessing them often requires that infrastructure (dams, canals, etc.) be built in the countries in which the resource originates, and that pollution control procedures be implemented there. Such resources are

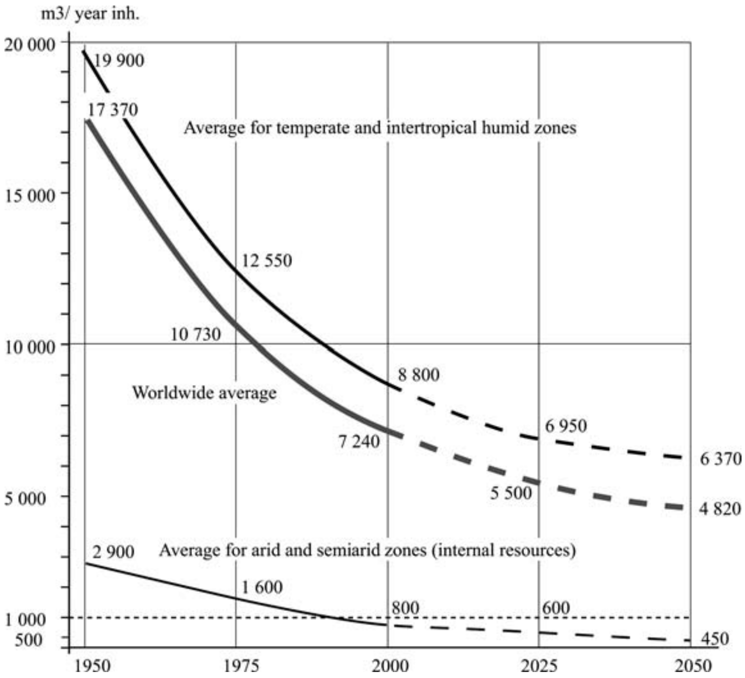

Fig. 13.4 Evolutions from 1950–2000 and projections for 2025 and 2050 of average per capita water resources (natural, renewable) in humid zones and in arid and semiarid zones across the world

often shared with countries that are either downstream (e.g., Sudan and Syria) or geographically opposite where rivers mark borders (e.g., Mauritania/Senegal and South Africa/Namibia).

- Substantial aquifers with very low rates of renewal can be defined as nonrenewable (NR) resources. That does not mean that reserves are not renewed at all or that such aquifers are entirely disconnected from renewable resource systems. It means that reserves take a good deal longer to replenish than they do in aquifers with renewable resources. The criterion currently adopted to define a nonrenewable aquifer is a global annual renewal rate of 1% or less. It would, in other words, take at least 100 years for the reserves of such an aquifer to be refilled. Naturally, the lower the rate of renewal, the longer it takes for reserves to be replenished. Consequently, much—perhaps even most—of the water in such aquifers is likely to have been there prior to the contemporary water cycle (twentieth century), hence the term "fossil water." The term "prehistoric" might be more appropriate. NR resources are not water courses but rather reserves similar to mineral deposits like coal and hydrocarbons. They are portions of subterranean water reserves that have infinitely small rates of renewability,[1] with a duration of thousands or tens of thousands of years. They can be economically extracted in an environmentally friendly way. These conditions most often exist in arid and semiarid zones,

Table 13.2 Comparative data concerning various countries in arid and semiarid zones

Predominant type of water resource	Country	GDP/ per cap. 2001 US\$[a]	Contribution of agriculture to GDP 2000 % (WRI 2002–2004)[b]	Average annual precipitation (mm)[c] (FAO/ AQUASTAT 2005)	Total real sustainable water resources (FAO, TARWR)[d]		TARWR percentage		Water use in 2000 or closest year		Supply in nonrenewable resources as a % of total water use	Supply in nonconventional resources		Gross virtual water imports[f]		Green water potential estimated in km^3 per year[g]
					Average km^3 per year	m^3 per inhabitant (2000)	internal	external	total km^3 per year cf.WRI 2005	Per capita (cf.population 2004) m^3 per year		Reuse km^3 per year[e]	Dessalement km^3/an	En km^3 per year	En %	
Internal renewable resources	Iran	1680	19	228	137.5	1955	93	7	72.9	1097	0		0.17	7.4	5	30
	Jordan	1750	2	111	0.9	179	78	22	0.75	202	10	0.07	0.002	4.6	523	0.4
	Kazakhstan	1350	9	250	109.6	6778	69	31	35	2238	0	0.27	1.3	0.2	ϵ	80
	Tunisia	2070	12	207	4.6	482	91	9	2.7	286	24	0.19	0.04	4.1	89	13.5
	Yemen	450	15	167	4.1	223	100	0	6.6	368	0		0.03	1.6	39	2.5
External renewable resources	Botswana	3100	4	416	14.4	9345	20	80	0.1	81	∼1	0	0			1
	Egypt	1530	17	51	58.3	859	3	97	71.7	1013	1	13.3[d]	0.03	19.3	33	1
	Iraq	(98)860		216	75.4	3287	47	53	42.8	1839	0		0.12	1.6	2	7
	Israel	16075		435	1.7	276	47	53	2	338		0.27	0.085	6.2	369	1.5
	Mauritania	360	22	92	11.4	4278	4	96	1.7	642	8		0.002	0.4	3	0.5
	Uzbekistan	550	35	206	50.4	2026	32	68	58.3	2342	0	4.5[d]		0.8	2	8
	Pakistan	420	26	494	222.7	2961	22	78	169.4	1187	0			2.6	1	90
	Turkmenistan	950	27	161	24.7	5218	6	94	24.6	5308	0	0.08		0.1	1	2.5
Nonrenewable resources	Saudi Arabia	8460	7	59	2.4	118	100	0	23.8	1170	86	0.24	1	13.1	545	0.2
	Algeria	1650	9	89	14.3	478	96	4	4.87	161	34		0.1	10.5	90	25
	Libya	(98)6830		56	0.6	113	100	0	4.8	919	67		0.23	4.4	730	0.3

Notes:

a. Source: World Bank 2003

b. WRI 2002–04, mostly irrigated agriculture

c. FAO: Food and Agriculture Organization/AQUASTAT 2005, average in space and time

d. TARWR: Total actual renewable water resources (natural internal resources + real external resources), FAO 2003 ("blue water")

e. Source: A.K. Chapagain and Hoekstra 2002, average figures 1995–1999

f. Including agricultural drainage water

g. Average real annual evaporation–transpiration from arable land.

Table 13.3 Dependency ratios of external resources

Country	Dependency ratio (%)
Egypt	97
Turkmenistan	97
Mauritania	96.5
Botswana	80
Syria	80
Uzbekistan	77
Sudan	77
Pakistan	76.5
Namibia	66
Israel	55
Iraq	53

Source: FAO base AQUASTAT 2003

which are very poor in renewable water resources and aquatic ecosystems worthy of conservation (UNESCO 2001).

From an economic point of view, NR resources can be exploited using the groundwater mining technique. A far greater quantity of water can be extracted using this method—and for a far longer period of time in terms of the human development of water uses—than by collecting even all the new water entering a given aquifer, or, in other words, all renewable resources. NR resources are defined in terms of extractible reserves, similar to other nonrenewable mineral raw materials. The term extractible refers at once to technological and economic feasibility criteria and to the absence of significant external effects and impacts (UNESCO/Foster and Loucks 2005). Such reserves of extractible subterranean water are a function of geological conditions, such as the existence of extensive, generally subterranean, aquiferous reservoirs that can be exploited by drilling, under high pressure, wells between a few hundred meters and, occasionally, more than 2,000 m deep. These reserves often can contain thousands of square kilometers of water, although they are considerably smaller than the total volume of existing subterranean water resources, most of which are impossible to exploit due to inaccessibility, depth, salinity, and other factors. These reserves can only be converted into resources for limited periods of time. As in any mining operation, these periods depend on the quantity of water extracted. At best, they can last only a few decades before they are exhausted.

The world's major aquifers that provide notable NR resources in arid and semiarid zones are found in Saharan basins in Africa and in the Arabian Peninsula and Australia (Fig. 13.5). Their principal characteristics are outlined in Table 13.4. At present, approximately 30 km^2 per year is extracted from these resources, which are almost entirely concentrated in arid and semiarid zones. Four-fifths of them are found in three countries: Saudi Arabia, Libya, and Algeria. Several countries in arid and semiarid zones currently derive a major or substantial percentage of their water supplies from NR resources: 86% in Saudi Arabia,

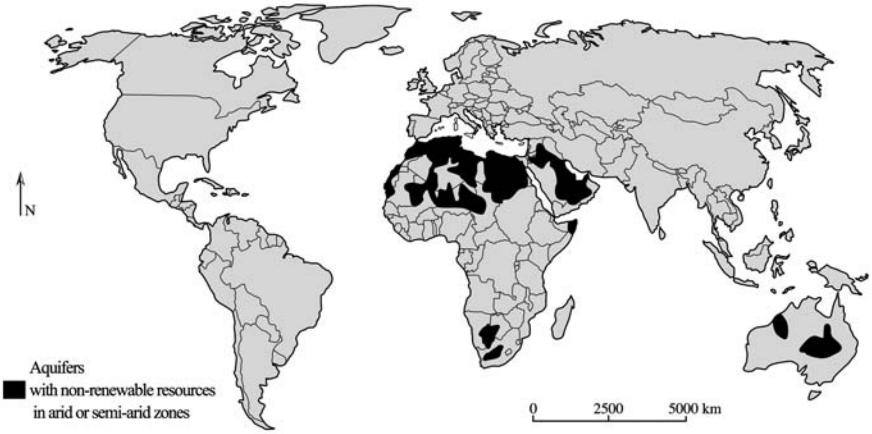

Fig. 13.5 Nonrenewable subterranean resources. The world's major deposits~~~Source: WHYMAP, I. Zekster 1999

approximately 85% in Algerian Sahara, 74% in the United Arab Emirates, and 87% in Libya. Here again, the quantity of water used is often superior to and often greater than IR resources, especially in Saudi Arabia and Libya.

A comparative analysis of the relative impact of these three types of water resources on the largest countries located in arid and semiarid zones reveals a number of major differences. The quantity of ER and/or NR resources can, in some measure, be used to explain the level of economic development—or at least the level of water supply security—of countries with negligible IR resources. In such countries, security of the water supply is now often guaranteed by a fourth kind of resource, virtual water, which is associated with the importation of food products (see Chapter 7). However, this phenomenon is tied to the economic capacity of such countries; the poorer they are, the less they are able to import. In countries that are at once very poor in water resources but very rich in exportable products such as oil and its derivatives, virtual water imports are significantly higher than conventional internal resources (Fig. 13.6).

13.2 Consequences for Water Management

In IR resources countries, water is a limiting factor in terms of development (but only to the extent that development is mainly based on irrigated agriculture and other activities that use a great deal of water) and in a context of population growth and, correspondingly, less available water per capita. In arid and semiarid zones, traditional societies have developed a complex system for managing the coexistence of pastoral nomadism and irrigated agriculture in oasis zones. Such societies have long existed without any appreciable form of demographic or economic growth. Most of

Table 13.4 Nonrenewable subterranean resources: estimates in various countries in arid and semiarid zones

Country	Aquifer(s)	Estimated volume of useable reserves (km^3)*	Current use (km^3 per year)
Algeria	North Sahara Aquifer System (SASS/NWSAS)	900	1.68 (2000)
Saudi Arabia	Arabian Multilayered Aquifer syst. (incl. Saq Aquifer)	500–2,000	13.5 (1995)
			20.47 (2000)
Australia	Great Artesian Basin	170	0.63 (2000)
Botswana	Karoo Sandstone. Central Kalahari	86 (en 30 ans)	ϵ (∼0,00005)
Egypt	Nubian Sandstone Aquifer system (avec post Nubian Aq. System.)	5,367	0.9 (2002)
United Arab Emirates	Arabian Multilayered Aquifer system	5	1.57 (1995–1996)
Israel	Nubian Sandstone Aquifer /Negev	(total: 20)	0.05 (2000)
Jordan	Disi Aquifer (Saq)	6.25	0.35 (1998)
Libya	Nubian Sandstone Aquifer system (with post Nubian Aq. Syst.) North West Sahara Aquifer System (NWSAS) Murzuk Basin	$\left.\begin{array}{r}4{,}850\\250\\60-80\end{array}\right\}5{,}170$	$\left.\begin{array}{r}0.58\\0.55\\1.75\end{array}\right\}2.9(2000)$
Mali	Lullemeden Multilayered Aquifer system (CI) Bassin de Taoudeni-Tanezrouft	∼100	0.0013 (2000)
		–	0.2 (2000)
Mauritania	Aquifère Maestrichtien	∼3	0.09 (2003)
Niger	Lullemeden Multilayered Aquifer system (Continental Intercalaire)	250–550	0.008 (2000)
	Chad Basin Aquifer System (CT Hamadian) Pliocene Manga	45	ϵ
Qatar	Arabian Multilayered Aquifer system	2,5	0.15 (1995)
Sudan	Nubian Sandstone Aquifer	2,610	0.41 (1998)
Chad	Nubian Sandstone Aquifer Chad Basin Aquifer System (CT Hamadian +CI)	$\left.\begin{array}{r}1{,}630\\220\end{array}\right\}1{,}850$	ϵ
			0.11 (2000)
Tunisia	Système aquifère du Sahara septentrional (SASS)	130	0.46 (2000)

* Clearly, evaluation criteria vary from country to country

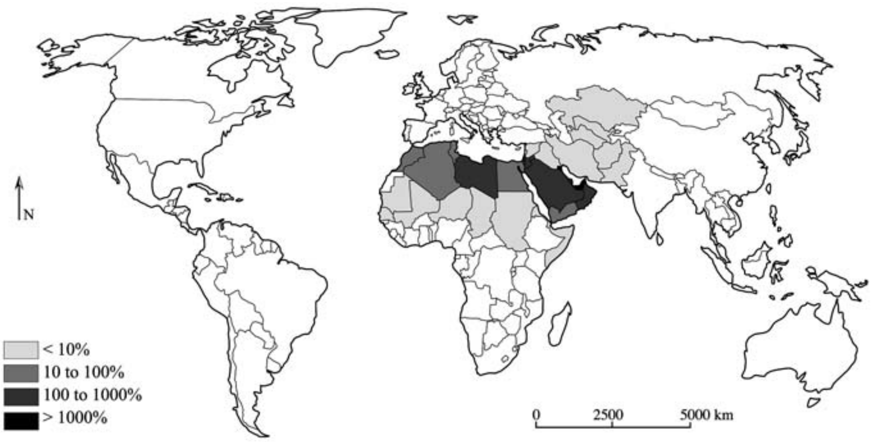

Fig. 13.6 Gross imports of virtual water deduced from average quantity of food imports (1995–1999) compared to internal and external renewable water resources (TARWR, FAO/AQUASTAT) in arid and semiarid zones (expressed as a percentage)

the knowledge those societies have acquired could be used in rethinking the way "developing" societies use water, but such practices would adversely affect growth (Georgescu-Roegen 1979).[2] Under IR resources conditions, development based on water extracted from subterranean deposits is not sustainable in the medium to long term. It is, moreover, subject to changes in market conditions. Furthermore, this kind of development frequently encourages the over-exploitation of renewable but limited subterranean water resources, which are merely a temporary source of growth in countries including Iran, coastal Libya, Morocco, Oman, and Syria.

Because the use of ER resources is mainly agricultural, ER countries benefit from abundant resources, which help meet the food needs of their growing populations. However, the long-term uncertainties and risks of conflict concerning the way in which these common resources are shared with countries located either upstream or downstream, as well as constraints induced by their conservation (power politics), may influence development. Uncertainties of this type can, in fact, lead to a kind of less ambitious but more sustainable form of "co-development."[3]

NR resources countries in the short term can have greater access to water, but that access is not sustainable. Generally inseparable from the production and export of hydrocarbons, the increase in the practice of extracting fossil water is more a result of, rather than a factor in, development encouraged temporarily by oil revenue. This is particularly the case in Saudi Arabia, Libya, and Algeria, three countries which together account for 80% of the world's fossil water extraction. In the long term, subterranean oil and water resources are likely to run out, a kind of double-whammy that is likely to cause serious socioeconomic repercussions. The temporary advantages offered by extractible water deposits and the kind of hydro-agricultural development they make possible (a decrease in the amount of food imported and the export of certain agricultural products) could—and should—contribute to laying the groundwork for a transition to new, nonconventional sources of water supply such as desalination. However, such approaches are costly in terms of energy—which most often relies on nonrenewable resources or exports—with the same constraints as ER resources. Nevertheless, these advantages should above all facilitate a transition towards sustainable forms of development that are less dependent on water and more focused on virtual water. Strategic choices concerning the exploitation of water resources that are not renewable in the long term—choices concerning intensity and duration—are based on alternatives between medium-term profits and long-term profits of an "inter-generational" nature (Biswas and Biswas 1982; Margat 2008).

13.3 Impacts on Development

Comparative data concerning the principal countries located in arid or semiarid zones reveal a number of similarities and differences. In particular, the economic weight of irrigated agriculture, as a percentage of gross national product, is generally higher in countries benefiting from ER resources that substantially increase their total per capita resources. This is true in Central Asia, Pakistan, and Egypt, where per capita water use also is highest. In addition, imports of virtual water are highest in countries in which IR and NR resources are predominant (Chapagain and Hoekstra 2002). Most of these countries, however, are oil exporters. No links have been discerned between the relative importance of green water and the contribution of agriculture to development, the rate of supply from NR resources, and imports of virtual water.

Insofar as nonconventional water supplies are concerned, although their use is increasing substantially, they generally account for only a tiny percentage of total water use: desalination rarely accounts for more than 1%. Saudi Arabia, Libya, and Israel have the highest figures, with 4–5% used exclusively to provide drinking water. The reuse of wastewater is only significant in the case of drainage water used for irrigation purposes. Egypt is an exceptional case; 19% of all water used for irrigation comes from this source. The relative use of nonconventional supplies does not appear to be linked to dominant conventional sources.

The variety of types of predominant water resources and the differences in resulting total water resources have a visible impact on demographic pressure, the influence of irrigated agriculture, and other factors in terms of explaining current differences in economic development. In all cases, development and food security seem to be highly dependent on trade with developed countries located in humid zones. In the long term, differences in variously sustainable sources of supply may have the greatest impact on development. Conditions of aridity create various kinds of very strong dependence, whether they are linked to the economic impact of income from mining—the extraction and export of nonrenewable raw materials and/or the extraction of nonrenewable water resources—or to more or less precarious "imports" of water. The inevitable depletion of such mined resources and/or the risk of external water resources drying up will engender serious crises in sustainable development if development does not adapt to the scarcity of renewable water sources. The cause of development in arid zones would doubtless be better served by the export of human expertise rather than on the export of finite raw materials.

Notes

1. The renewal of an aquiferous reservoir is the relationship between the rate at which it is naturally supplied and the reserve of water constituting it, expressed as an average annual rate (%) or as a duration (the number of years it takes for accumulated inflows to provide a quantity of water equal to the original reserve).
2. Editor's note: see, for example, the Mexico 2006 4th World Water Forum, "Local Action for a Global Challenge."
3. Editor's note: see UNESCO/IHP (International Hydrological Programme), http://typo38.unesco.org/index.php?id=240

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Chapter 14
Conjunctive Water Management in the US Southwest

Juan Valdes and Thomas Maddock III

Abstract Water demands in the US Southwest have been subject to great pressures due to explosive population growth and climate variability that has produced decadal droughts. These pressures have led to unsustainable use of surface water and groundwater, forcing states to adopt conjunctive management of ground and surface water systems. Unfortunately, federal and state laws have not kept pace with the scientific development of management strategies. A series of examples are presented to illustrate some successes and failures of integration of surface water and groundwater management and its accompanying legal implications.

Keywords Conjunctive water management · Prior appropriation · Riparian rights · Stream depletion · US Southwest

14.1 Conjunctive Management Processes: An Introduction

Water resources management in the United States varies greatly due to climatic, geologic, hydrologic, and political reasons. The more humid eastern part of the country developed a system of water rights based on riparian rights for both surface water and groundwater, whereas the western US developed a more complex system.

The US Southwest, comprising the states of New Mexico, Arizona, California, Colorado, Nevada, and Utah, is experiencing rapid population growth that far exceeds the rate of growth in the country as a whole (Fig. 14.1). This increase is expected to continue well into this century.

Only California has a growth rate similar to that of the U.S because of the slow relative growth of its water-rich northern counties; arid Southern California is growing at a rate similar to those of the neighboring states. Approximately 45 million people were living in the Southwest in 1995, and the number is expected to rise to 64 million by 2025. These demographic pressures, combined with decadal

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G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
DOI 10.1007/978-90-481-2776-4_14, © Springer Science+Business Media B.V. 2010

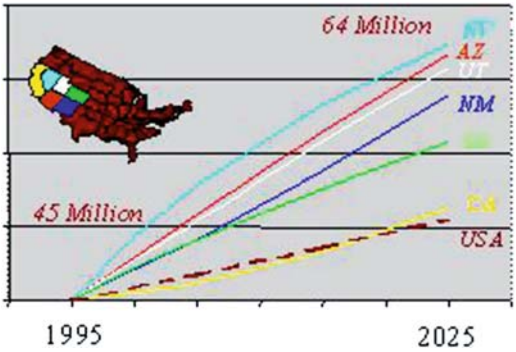

Fig. 14.1 Population growth rates in the Southwest US (See also Plate 13 on p. 344 in the color plate section)

droughts, have led to the unsustainable use of surface water and groundwater, forcing states to adopt conjunctive water management—the joint use of these water systems. Improvements to water law have not kept pace with the increases in population, and modifications of the regulatory framework have not always been closely aligned with hydrologic science. It has been necessary to adapt the legal framework in the region and to adopt some legal terms that are closely related to hydrologic science.

14.1.1 Motivation

The US Southwest has always been driven by a scarcity of water, and this scarcity changed the region's water law. The law of the West—known as prior appropriation doctrine—had its birth in the California Gold Rush in the mid-1850s. It transformed the foundation of this scarcity-driven society. With the amount of available stream water dwarfed by the vastness of the West's barren landscape, the doctrine became the manifesto that no drop of water should be allowed to course to the sea unused.

By the end of the nineteenth century, irrigators, miners, and municipalities already were draining western streams dry so that during lean years, the junior-most claim holders were left with little or no water. Wet years were a different story altogether. Thirsty settlers watched in dismay as spring snowmelt rippled and roared through swollen river channels and out to sea. Scarcity once again drove the West, this time in the form of the Reclamation Act of 1902. Many dams were built quickly and the West watched contentedly as the annual spring surge to the sea was stopped short of its destination, transforming deep, dark canyons into vast pools of cloudless turquoise. Figure 14.2 shows that Colorado River flows that reach the Sea of Cortez in Mexico have become nearly nonexistent since the last dam on the Colorado was built.

Still, this water was not enough. Scarcity drove westerners into the ground to suck water reserves to the surface as if the aquifers were infinite. With the apparition of scarcity, the West has continued to reinvent law, clog the river-carved canyons,

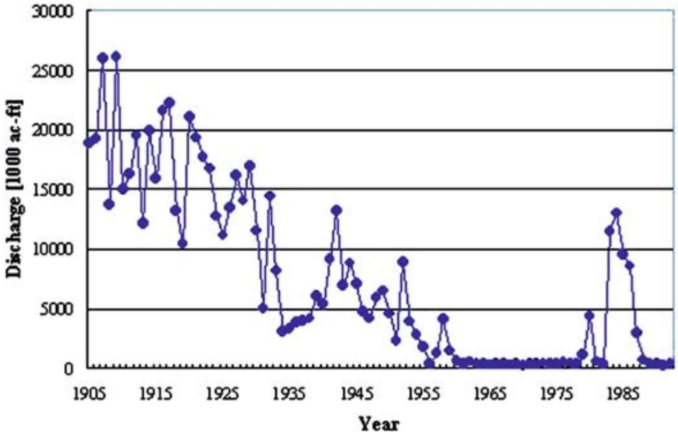

Fig. 14.2 Mean annual discharges of the Colorado River below all dams

and funnel waters up from hundreds of feet below. Now all the native sources of water have been tapped: streamflows have dwindled, the best canyons have been dammed, and aquifer water levels are falling fast. The issue is not only quantity but also quality, as shown by the Colorado River—which has a salinity concentration of 80 parts per million (ppm) at its headwaters and an average concentration of 800 ppm where it reaches the Colorado River Delta—and the Rio Grande, which has a salinity of about 200 ppm at its headwaters in Colorado and up to 2,400 ppm at the Texas border with New Mexico.

14.1.1.1 Stream Depletions

The West's perennial streamflow has diminished by more than 50% over the past century (85% in Arizona, Glennon and Maddock 1994) in the wake of numerous significant surface water projects and groundwater pumping. Despite the enormity of the problem, the disappearance of western streams has occurred largely unnoticed for three reasons. First, the process of stream depletion is not apparent to the human eye. Whereas it is very easy to observe the amount of water being channeled from the stream through a surface-diversion gate, it is impossible to visually separate the stream component of water being discharged from a near-stream well. Second, the amount of stream depletion is obscured by high-flow events and droughts. Summer monsoon storms and snowmelt can fill western streams to their banks regardless of the existence of groundwater pumping, and a sustained drought substantially reduces streamflow and may mask the surface water depletions. Third, the effect of groundwater pumping on a nearby stream is delayed over time. In some cases, water pumping may occur for decades before its effect is evident on a connected stream system. Furthermore, cessation of pumping will not prevent the eventual depletion of water from the stream due to the previous pumping.

14.1.1.2 Surface Water Rights

There are two principles for surface water rights in the US: riparian rights and prior appropriation. For riparian rights, which are predominant in the eastern US, the main concept is that land ownership also entitles the owner to use of the water adjacent to it. Because a strict interpretation is not feasible, riparian rights usually allow the owners of property adjacent to a river to divert water for reasonable use (Wurbs and James 2002). In contrast, the surface water rights for the western US fall under the principle of prior appropriation. In this case, water rights are not inherent in land ownership but rather are based on seniority (i.e., when the water was first appropriated). Prior appropriation allows water rights to exceed average flows and it requires a careful review of the historic records, which may be a difficult task. Because of this, states have established a procedure for adjudicating water rights.

The principle of prior appropriation has three basic components. The first is the principle of "first in time is first in right" (i.e., when a deficit occurs, owners of the most junior rights are the first to have their water resources curtailed). The second principle is "use it or lose it," which allows water rights to be lost if the resource is not used. The third is "water must be used beneficially."

Both the riparian and prior appropriation doctrines require the beneficial use of water, a requirement that has ramifications for instream flows relative to the protection of riparian areas or endangered species.

14.1.1.3 Groundwater Development and the Conflicts with Prior Appropriation

As indicated above, surface water is no longer the sole source of water in the West. Technological advances have allowed for efficient extraction of water from the subsurface: the development of the high-yield centrifugal pumps made it physically possible; rural electrification brought forth the existence of cheap hydropower that made it feasible; and advances in well drilling techniques enabled its quick proliferation.

Because the appropriation doctrine was generally geared to surface water, its applicability to groundwater was neither appreciated nor understood. Groundwater laws were generally governed by a reasonable use doctrine based on property right statutes. Groundwater had been considered appurtenant to the adjacent land, thus protected by private property rights. In such cases, the right holder was the owner of the land above the water. Although the efficiency of groundwater extraction may have varied from location to location, groundwater could be extracted almost anywhere in an alluvial valley, thus nullifying the need to import water from an outside source, such as a stream. The quantity of the extraction was limited by "reasonable" use. However, the degree of reasonableness was measured relative to other property owners—in other words, only other groundwater pumpers. Currently, the reasonable use principle is losing favor among the western states, which are adopting integrated groundwater and surface water prior appropriation principles.

Although ostensibly reminiscent of riparian rights, the groundwater code reflects the same economic desire to maximize exploitation of the resource as the appropriation doctrine does. Indeed, the development of groundwater in the West seemed to open the door to an infinite water supply, one forever freed from the finite supply of the stream. With the increased use of groundwater, the underlying assumption of the prior appropriation doctrine, as applied to surface water, began to break down. An appropriation doctrine that did not include the groundwater sources was ill-suited for the evolving technological environment that enabled groundwater pumping. Near-stream well pumping could diminish streamflow, either by direct infiltration from the stream or interception of groundwater before it reached the streambed. Put into the broad perspective of the prior appropriation doctrine, many groundwater pumpers were junior surface water holders. Their ability to tap into a reliable reservoir of water effectively gave them priority to the entire water system by the simple flick of a switch.

As pumping has increased, many western states have slowly recognized the interconnectedness of all waters and the inappropriateness of separate laws for both surface water and groundwater. New Mexico and Colorado, for example, quickly adopted more expansive views of the appropriation doctrine, making all waters appropriable. California, Arizona, and Texas, meanwhile, are still plagued with bifurcated water law.

14.1.2 Interaction Between Surface Water and Groundwater

Conjunctive water management on state and local levels is a relatively new political phenomenon. This type of management has evolved, in part, in response to growing populations with ever-increasing and often conflicting water demands. In addition, a more sophisticated technical understanding of the physical link between groundwater and surface water has led water managers to reconsider historical strategies for solving water supply problems. In light of growing demand and improved technologies, some western states have begun the transition from crisis-oriented water management to one of long-term planning for population growth and environmental protection. This planning process requires that the constituents of a region define their water goals and objectives so that various approaches to conjunctive management can be evaluated for their suitability to that particular physical and social-political environment.

A primitive legal recognition of the physical connection between groundwater and surface water extends back to the late 1920s, but active management of groundwater and surface water as inseparable and highly interdependent resources occurred much later in the western US. In contrast to the speed with which scientific understanding of the physical interrelatedness of groundwater and surface water has evolved, the separate and conflicting legal systems governing the two natural resources have been slow to converge.

Some of the southwestern states have been very reluctant to change their groundwater and surface water laws. For example, California and Arizona use a treatise entitled *The Law of Irrigation and Water Rights* by Clesson S. Kinney (1912) to settle conflicts produced by the interactions of surface water and groundwater. Kinney, a Utah attorney and not a hydrologist, divided groundwater flow into courses of known and unknown channels of water. He further classified the known ground channel water as independent or dependent, with the former being uninfluenced by streams and the latter constituting subflow of the streams. California uses the word underflow instead of subflow, but they are the same. Kinney referred to one form of independent water as “tributary groundwater.” This was the groundwater that had “not yet reached the channels of the water courses to which they are tributary.” Thus, Kinney created a legal dichotomy of groundwater that interacts with surface water—subflow (or underflow) and tributary groundwater.

The Arizona and California courts decided that Kinney’s subflow/underflow is appropriable like surface water, but all other forms of Kinney’s groundwater are not. To the courts, subflow/underflow was loosely defined as “waters that slowly find their way through sands and gravels [of] the bed of the stream, or [through] lands under or immediately adjacent to the stream” (*Maricopa County v. Southwest Cotton* 1931). Both California and Arizona have been trying to define underflow and subflow more accurately since they accepted the Kinney dichotomy (see Sax et al. 1991 for California; see Arizona Supreme Court 2000 for Arizona).

Having the courts define terms such as subflow or tributary groundwater without evidence from modern hydrology creates artificial divisions of groundwater that only perpetuate the bifurcated surface water and groundwater laws and convoluted water management. Only when these two states recognize the interaction between surface water and groundwater as a continuum will they be able to create a unified system of water law, as have many of their sister states.

14.2 Water Resources Management in Semiarid Regions

14.2.1 Southwestern Water Resources Management

The management of water resources in the US has traditionally fallen to the states. Most states have an institutional entity that manages water resources. In the West, most have a state engineer or water director who is in charge of enforcing rules or laws that have been enacted to govern the extraction, diversion, and distribution of water. For example, New Mexico, Colorado, and Kansas have state engineers. Arizona, Texas, and California have water management agencies with directors. Unfortunately, many of the states have within their managing entities the same artificial breakdowns in water type. For example, the Arizona Department of Water Resources has a division that manages groundwater, another that manages surface water rights, and still another that manages hydrology, giving one the impression that hydrology in Arizona has nothing to do with groundwater or surface water.

The surface water supply system of the southwestern US was largely developed with funding from the federal government. With the Reclamation Act at the beginning of the twentieth century, a series of dams was designed, funded, and built throughout the western US, primarily to supply water for agriculture. The principal federal agency responsible for the design and building of these dams was the US Bureau of Reclamation (USBR); the US Army Corps of Engineers (USACE) played a lesser role. USBR entered into contracts with farmers of the region where a dam was to be built. The farmers purchased irrigation water from USBR at a price that reflected repayment of the facility. They also were guaranteed water, if available. The implication was that after the dams were paid off, ownership would fall to the farmers. When it became clear that more funds and organization were necessary to help in the operation, maintenance, and replacement of the dams than the individual farmers could sustain, the farmers formed irrigation districts. The irrigation districts had powers to raise money.

The issue of who owns the paid-off dams is of concern today. However, as a rule, USBR controls releases from the reservoirs to the river or stream and the irrigation district or states control diversions from the streams or rivers to the canal, laterals, and the field. States have the right to manage intrastate stream activities; in most cases, an irrigation district is treated as a single user if it is located along a state-managed river or stream, and the state allows the district to internally distribute the water. This internal distribution is legitimized by the irrigation district making offers of water to the farmers and wrapping up the process in adjudication.

The larger rivers of the southwestern US—the Colorado, Rio Grande, Pecos, Arkansas, and Platte—all flow through several states. Because water laws in states vary, the states have entered into agreements called compacts. For example, Colorado, New Mexico, and Texas have a compact on the Rio Grande; Colorado, Nevada, California, Arizona, New Mexico, Utah, and Wyoming have a compact on the Colorado River; and Colorado and Kansas have a compact on the Arkansas River. The US Congress ratifies the compacts, and disputes on a compact river between states usually end up in the US Supreme Court, which has immediate jurisdiction.

14.2.2 Water Management Examples

14.2.2.1 Impact of Droughts on Water Management

Of all aspects of climate of the US Southwest, drought is the most difficult phenomenon to characterize and predict (González and Valdés 2004 and 2006). González and Valdés (2003) used paleoclimatic records to extend the instrumental record for drought analysis in south Texas. Understanding the cause of drought and being able to predict its occurrence would be extremely valuable. For example, an extensive study completed in Texas in 1994 showed that a severe one-year drought that constrained water supplies by 15% would cost the state's economy \$15 billion in direct effects and \$25 to \$45 billion in indirect effects. This hypothetical drought is similar to one that Texas suffered in the 1950s. In the study, the impacts were only quantified for one year, but the drought of the 1950s, like many others in the region, was a multi-year drought.

In spite of the difficulties involved in predicting the timing and severity of the droughts, a relatively reliable prediction of a major drought event would undoubtedly prevent many adverse drought-related consequences. The sudden onset of a severe drought in 1996, which brought disaster to Texas agriculture, motivated the state's legislature to approve Senate Bill 1 (SB 1) in its 1997 session. The designation of SB 1 indicates the primacy of the legislation to the state of Texas. SB 1 directs the Texas Water Development Board (TWDB) "to divide the state into water planning regions and appoint volunteer planning group members to represent each of eleven identified user groups including: agriculture, public, counties, municipalities, industries, environmental, small businesses, electric generating utilities, river authorities, water districts, and water utilities." The groups are required to develop a regional water plan and review it every five subsequent years. TWDB is mandated to edit these regional plans and form a State Water Plan[1].

SB 1 also states that groundwater conservation districts can be created to "provide for the conservation, preservation, protection, recharging, and prevention of waste of groundwater reservoirs or their subdivisions." The districts must develop comprehensive management plans, in coordination with the surface water management entities, and address the following activities:

- providing the most efficient use of groundwater
- controlling and preventing waste of groundwater
- controlling and preventing subsidence
- addressing conjunctive surface water management issues
- addressing natural resource issues

A groundwater district may require the following from a well permit application:

- a statement of the nature and purpose of the proposed use and the amount of water to be used for each purpose
- a water conservation plan or a declaration that the applicant will comply with the district's management plan
- the location of each well and the estimated rate at which water will be withdrawn

SB 1 also recognizes Conservation Water Districts as the preferred entity for managing groundwater in Texas. The 77th Texas Legislature further expanded SB 1 when it approved SB 2, which provides further clarifications for the groundwater management districts. SB 2 requires the TWDB to designate groundwater management areas for all major and minor aquifers in the state. Sixteen such groundwater management areas have since been defined.

14.2.2.2 Surface Water/Groundwater Interaction: Edwards Aquifer System

The Edwards Aquifer in central Texas exemplifies the coupling of surface water and groundwater flows and shows the impact of the different legal principles that govern both in the US. Loaiciga et al. (1998, 2000) carried out an evaluation of the impact of climate change in the Edwards Balcones Fault Zone (BFZ) aquifer in the San Antonio and Austin regions of Texas. Their study was a continuation of a previous study in which several basins in the US were analyzed for potential climate change impacts in a project sponsored by the US Environmental Protection Agency (EPA) (Loaiciga et al. 1996).

The Edwards Aquifer is composed of a recharge area (1,100 mi^2) and a confined zone (5,009 mi^2). The runoff that originates in the catchment area flows through the recharge area in the aquifer and has total dissolved solid (TDS) values ranging from 350 mg/L to more than 1,000 mg/L (Maclay and Land 1987). Groundwater moves generally from west to east and discharges in a number of large springs, of which the Comal and San Marcos are the largest. These groundwater-fed springs have average flows of 284 cubic feet per second (cfs), or 8.05 m^3/sec, and 170 cfs (4.82 m^3/sec), respectively (USFWS 1996), with a uniform temperature of approximately 23°C.

This uniformity in discharge, temperature, and water chemistry has created one of the Southwest's most diverse aquatic ecosystems (Longley 1981; USFWS 1996), which includes the Edwards Aquifer and the ecosystems associated with the Comal and San Marcos springs and related springs, lakes, rivers, and caves. This unique ecosystem supported by the Edwards Aquifer habitat and springflows has been impacted by ever-increasing groundwater pumping, development, and recreational activities that affect water quality and modify species habitat in multiple ways (USFWS 1996; Glennon 2003). As a result of these activities, the following species have been designated as endangered under the Endangered Species Act (ESA): San Marcos gambusia (*Gambusia georgei*, a fish species), the fountain darter (*Etheostoma fonticola*), Texas wild rice (*Zizania texana*), and the Texas blind salamander (*Typhlomolge rathbuni*). The San Marcos salamander (*Eurycea nana*) has been included in the threatened species list (Campbell 1995; USFWS 1996). Thus one of the main ecological issues is the protection of these species from extinction; this affects both management and regulatory considerations in exploiting the Edwards Aquifer waters.

Loaiciga et al. (2000) addressed these concerns and built a decision support system (DSS) to evaluate the impact of demand growth under uncertain climatic variability and change in the Edwards Aquifer. The outputs of several general circulation models (GCMs) were used to represent the uncertainty in regional climate change forecasts. Historical data also were used to run climate scenarios (dry, normal, and wet) for several pumping schemes. An example of the results for dry conditions is shown in Fig. 14.3. The San Marcos springflows are shown under pumping scheme D1 (which maintains a 449,000 acre-feet (af)/yr or 553.8 Mm^3/yr constant pumping rate, which is the demand forecasted for year 2050 without any additional conservation measures) and the D2 scenario (no pumping). These two scenarios create upper and lower bounds to the impact on the springs of the region. Also shown are the San Marcos springflows for 1947–1959 and a 6,000 af/mon or 7.4 Mm^3/mon reference level, the lowest flow level to preserve the aquatic habitat.

Six more GCM results were used in addition to the GFDL 30 (Geophysical Fluid Dynamics Laboratory)[2] model to demonstrate the impact that variability in the

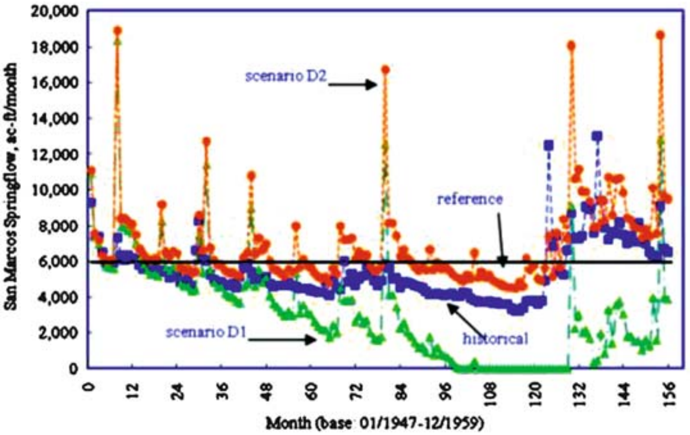

Fig. 14.3 Impact on San Marcos springflows of different pumping schemes under drought conditions. (Source: after Loaiciga et al. 2000)

different model predictions has on the springflows. The results showed significant variability.

In summary, the Loaiciga et al. study found that:

- the Edwards Aquifer is very vulnerable to climate change trends given existing groundwater use and predicted growth;
- a pumping level of 400,000 af/yr (493.4 Mm^3/yr) under average $2\times CO_2$ conditions (a doubling of carbon dioxide concentration) would preserve discharges at key springs above the severe-impact level most of the time;
- TWDB's pumping predictions for year 2050 (630,000 af/yr or 777.1 Mm^3/yr) would dry Comal Springs and impose frequent water shortages at San Marcos Springs; and
- under drought conditions in a $2\times CO_2$ climate, a maximum pumping of 140,000 af/yr (172.7 Mm^3/yr) would minimize aquifer impacts while providing a base level of water supply. However, no pumping strategy can prevent shortages at the San Marcos and Comal springs.

These pessimistic results were not widely appreciated in the region. This emphasizes the importance of sharing information throughout the modeling process and increasing the involvement of local institutions and stakeholders.

14.2.2.3 The Rio Grande Project: New Mexico and Texas

The origins of conflict between Texas and New Mexico on the reach of the Rio Grande that flows between Elephant Butte Dam in New Mexico and Fort Quitman in Texas originated with the Rio Grande Project. This project was authorized in 1905 to build Elephant Butte Dam and enhance a system of irrigation canals in southern New Mexico and west Texas. A year later, a treaty between the US and Mexico led to a distribution of waters of the Rio Grande between the two countries. The dam was completed in 1916; it was financed by the US federal government with money to be repaid by the farmers of New Mexico and Texas. Another dam, Caballo, was built in 1938 to trap water released from Elephant Butte Dam during the winter. Caballo Dam is a short distance downstream from Elephant Butte Dam, and irrigation releases occur only from Caballo.

The New Mexico portion of the project consisted of 90,640 ac (57%) and the Texas portion totaled 69,010 ac (43%). The division of water, even to this day, is based on these irrigated acreages and percentages. With the construction of canals and laterals invariably comes a rise in the water table that may lead to water logging. Accordingly, during the 1920s, a series of drains was incorporated that reduced the water table and returned flow to the river. It also became clear about this time that individual farmers could not pay back the federal government, so they organized into irrigation districts that were quasi-governmental agencies with taxing powers. The result was Elephant Butte Irrigation District (EBID) in New Mexico and El Paso County Water Improvement District No. 1 (EPCWID) in Texas (Fig. 14.4).

In 1938, Colorado, New Mexico, and Texas entered into the Rio Grande Compact, which apportions the waters of the river among the three states. The headwaters of the Rio Grande lie in the San Juan Mountains of Colorado. The river flows

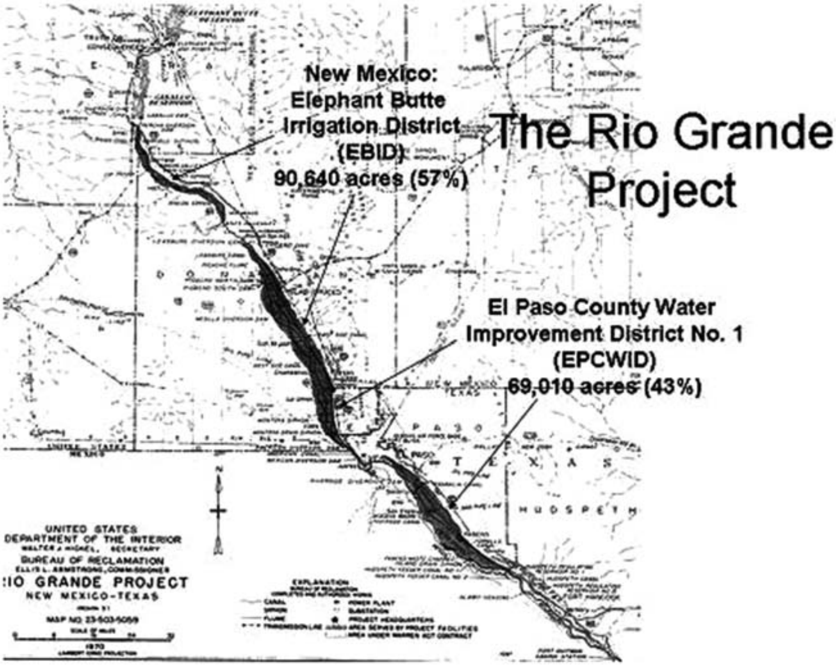

Fig. 14.4 The Rio Grande Project division of land between Texas and New Mexico

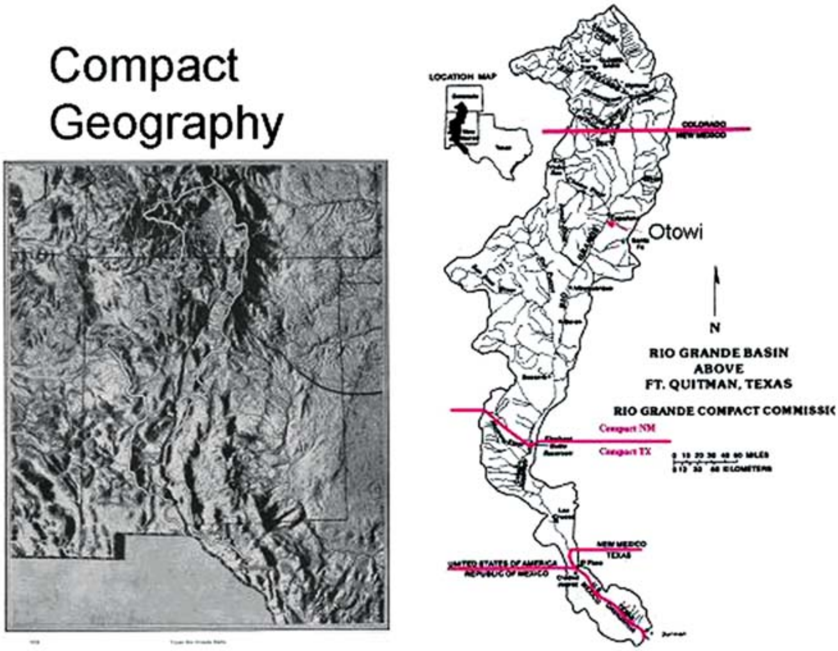

Fig. 14.5 Rio Grande Compact boundaries

south into New Mexico where its flow is enhanced from tributary inflow from the Chama River, continues south to Elephant Butte Dam, and crosses the border into Texas near El Paso. The compact area ends at Fort Quitman (Fig. 14.5).

The Rio Grande Project was included under the Texas portion of the compact, an assignment that sowed the seeds for later trouble between Texas and New Mexico because a large part of the Texas compact portion is in New Mexico. The compact empowered the USBR to operate the Rio Grande Project as a single entity. Each state in the compact has a commissioner who manages that state's portions. The commissioners for Colorado and New Mexico are the state engineers, while the Texas commissioner is a political appointee of the governor.

Initially, the compact's domain of interest was surface water issues, and groundwater issues were not specifically addressed. However, a drought persisted from 1951 through 1978, and the Rio Grande Project responded to short water supplies by developing groundwater wells. From this period of time, the USBR developed the "D1" and "D2" curves that projected delivery to the US farmlands along with the water diverted to Mexico (D1), and projected diversions to canal systems in the irrigation districts and Mexico (D2, see Fig. 14.6). The D1 curve has since been discarded and has been deemed pertinent only in determining the allocation to Mexico during droughts.

The D2 curve in Fig. 14.6 indicates that if 600,000 af of water is released from Caballo Reservoir, then 713,000 af of water (referred to as project water) would

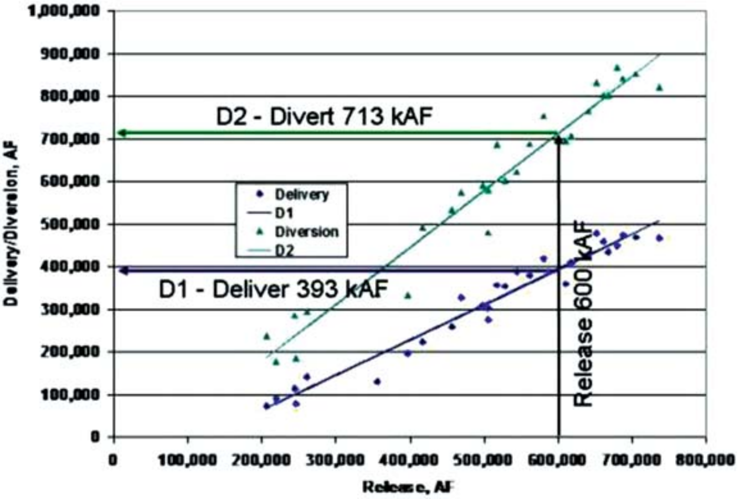

Fig. 14.6 The D1 and D2 curves used by the Rio Grande project (See also Plate 14 on p. 344 in the color plate section)

be diverted to the canal systems. The additional 113,000 af of water would be provided by the drains returning water to the river. Of the project water, 43% would be provided to Texas and 57% to New Mexico.

In the late 1970s, USBR began to suffer a series of budget cuts and political setbacks that ultimately relegated it to specifying only the releases from the Caballo Reservoir and forced the two irrigation districts to manage the diversions. The independence of the two districts from the USBR increased further when EBID paid off its construction loan in 1979 and EPCWID paid off its loan in 1980. An operating agreement (which covers both the operations and management of the system) became imperative.

In 1980, the city of El Paso applied for groundwater well permits in the New Mexico portion of aquifers in the Hueco Bolson and Mesilla Bolson basins, which aggravated issues between the two states. New Mexico denied the applications, a series of lawsuits was filed by El Paso, and the last lawsuit was dismissed in 1991. The court cases put further pressure on the irrigation districts to start negotiating an operating agreement. Mother Nature again intervened with an abundance of rain and full reservoirs from 1979 to 2002, taking pressure off the irrigation districts, at least until 1997.

During that year, any notions of civility between the two districts began to unravel. The problem began with USBR filing what is called a quiet title suit in federal court. The suit may have been quiet in the rest of the country, but it became extremely loud in New Mexico and west Texas. USBR feared that because EBID and EPCWID had paid off their construction loans, the districts would claim title to all project water. The USBR argued that because there was a treaty obligation to allocate water to Mexico, the US federal government should remain title holder of the project water. Because everyone was headed for court, it also seemed an opportune time for EPCWID to file a cross-claim alleging inequitable allocation of project water by USBR because of groundwater pumping in New Mexico. The case ended up in the hands of Judge William Deaton, a federal magistrate in Albuquerque, New Mexico.

The late 1990s began an era of dispute resolution, the idea being that a pleasant set of negotiations ought to be preferable to battling each other in the courtroom. Judge Deaton hired John Bickerman, a young dispute resolution expert from Washington DC. Bickerman's claim to fame at that time was having settled a dispute involving Lake Michigan by having the USACE change the flow direction of the Chicago River, reinforcing the old adage that water flows uphill to money.

So the three parties—EBID, EPCWID, and the USBR—sat down to negotiate. They began on a high note, with the Texas technical expert giving a well thought-out set of arguments to support EPCWID grievances, but unfortunately as time passed and less eloquent discussions ensued, the negotiations broke down; the participants made disparaging remarks about the intelligence of the others' ancestors. By 2000 the negotiations collapsed, and in 2001 the quiet title suit, with all its baggage, was dismissed without prejudice.

Things got uglier in 2001. The attorneys general of Texas and New Mexico and their respective state legislatures got involved, potentially escalating the litigation to the US Supreme Court. Each state's legislature appropriated millions of dollars to support the probable pending litigation. The New Mexico attorney general created what she called her "dream team," a group of highly reputable but expensive attorneys and consultants; Texas created a formidable counterpart.[3]

Even though the formal negotiations collapsed in 2001 and remained officially dormant for the next six years, the districts and technical representatives of the USBR were talking, sometimes in El Paso, sometimes in Las Cruces, New Mexico, and once in Tucson, Arizona, under the auspices of The National Science Foundation (NSF) Science and Technology Center for Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA). During these years some issues that were initially deemed important to the districts were found not to be. For example, year-round release was originally believed to be vital to EPCWID because of a potential conversion of agriculture water to urban water use for El Paso. Caballo Reservoir historically had released water during the irrigation season between March and October and made no releases during the non-irrigation season from November to February. At times, the only water one saw flowing in the Rio Grande below Caballo Dam down to Fort Quitman during the non-irrigation season were return flows from the drains and treated wastewater, and water quality was poor. However, by the 1990s, some limited releases from Caballo Reservoir were occurring as late as January, and the city of El Paso's interest in purchasing surface water waned.

Two critical negotiation points emerged from the discussions: carry-over storage and New Mexico groundwater pumping. Carry-over storage would allow each district to store water from an irrigation season and use it the following year. This would allow states to stockpile water for mini-droughts. This is also an important capability for EPCWID.

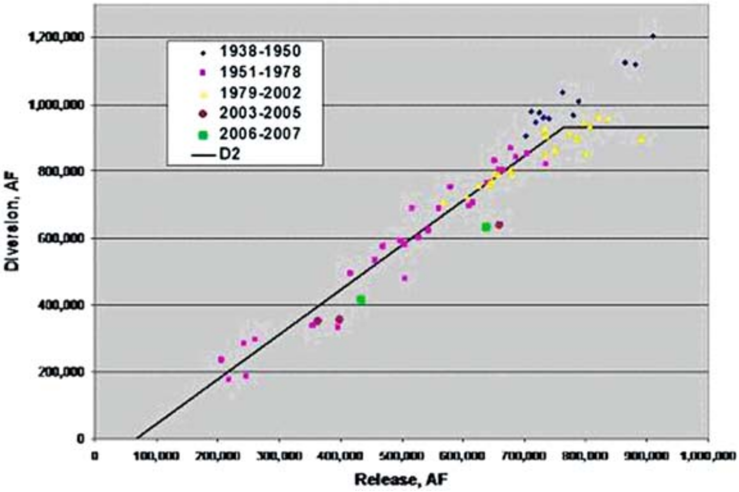

Fig. 14.7 Visualizing groundwater pumping impacts (See also Plate 15 on p. 345 in the color plate section)

EBID was well aware that groundwater pumping from the Mesilla and Rincon basins was depleting the river. The district had built a series of groundwater models over the years and could calculate estimates of these depletions. In fact, USBR's D2 curve, based on the data from 1951 to 1978, reflects groundwater pumping. Although the D2 curve has an embedded response to the major drought of the 1950s, the drought that started in 2003 proved even more severe.

Figure 14.7 shows that the diversions available for the releases from 2003 to 2006 were very short of what D2 predicted for the 1951–1978 condition. It indicates that groundwater depletions in New Mexico were reducing the drain return flows, thereby reducing the water supply available for diversion. El Paso was taking 43% of the hit for this reduction. New Mexico needed to ameliorate this loss to Texas.

From 2006 to 2008 the two districts and the USBR danced in and out of the lower-level US federal courts, always just avoiding the big swing into the US Supreme Court, and the technical groups and the district managers kept an ongoing dialogue. A big break for all involved came in 2006. The Texas governor appointed a young tax attorney, Pat Gordon, as the Texas Rio Grande Compact commissioner. Although perhaps not the most knowledgeable about the fine points of the water issues between the two irrigation districts, Gordon made it his undying ambition to get the two districts and the USBR to produce the seemingly unattainable: the Rio Grande Project operating agreement. Using sweet talk and hints of threats of coercion to all concerned, he did just that.

In 2006, the EBID proposed a new curve called D3, which tied EPCWID and Mexico allocations to project releases. The D3 curve predicts the amount of project water that EPCWID and Mexico should receive for annual releases from Caballo Reservoir. Ignoring carryover storage, EPCWID receives 43% of project water estimated from the old D2 curve, minus the allocation to Mexico. If the annual release from Caballo Reservoir was 600,000 af, the EPCWID should receive 43% of 600,000 af minus the allocation for Mexico (60,000 af), which is 280,790 af.

By February 2008, with Pat Gordon's continued pressure, an accord was reached. The key points were:

- EPCWID wanted and got carryover storage;
- EPCWID wanted and got protection from the impacts of excessive groundwater pumping by EBID, guaranteeing that EPCWID would receive the D3 allocation at the state line;
- EBID wanted and got D3 as the basis for allocation of project water;
- EBID wanted and got the right to provide the EPCWID allocation in the manner of its own choosing.

On February 14, 2008, 14 New Mexican and Texas farmers signed the operating agreement that ended a 29-year dispute and saved both states millions of dollars by avoiding a costly US Supreme Court case.

14.2.2.4 Domestic Wells

Practically every state exempts a category of wells from state regulation. The category focuses on groundwater used for domestic purposes, which might include some amount of irrigation, stock watering, and other designated uses. The statutory exemption rests on the policy judgment that it is simply not worth the time and trouble to require small domestic users to obtain a permit and a water right for uses that appear to be de minimis, or inconsequential, when compared to the enormous quantities of water used in the state for irrigation and other purposes (Glennon and Maddock 1997). The category of domestic wells was central to a lawsuit and an ensuing court ruling that has reverberated throughout the US West.

The Bounds family has been ranching and farming along the upper Mimbres River since 1869, and because of this early date, the Bounds have the senior-most right to surface water from the river. There are numerous other farms and ranches in the valley, so the river and groundwater are fully appropriated, if not over-appropriated. Surface water and groundwater of the Mimbres Basin have been adjudicated and closed since 1972, so no new water rights have been issued since that date; however, the adjudication did not include domestic wells. This apparent oversight stems from the 1954 New Mexico legislature mandating that the Office of the State Engineer "shall" issue domestic well permits and simultaneously exempt domestic well applications from notice and hearing requirements applicable to all other groundwater applications (N.M.S.A., Section 72-12-1). The problem is that the New Mexico Constitution (Article XVI, Section 2) states:

> The unappropriated water of every stream, perennial or torrential, within the State of New Mexico, is hereby declared to belong to the public and to be subject to appropriation for beneficial use, in accordance with the laws of the state. Priority appropriation shall give the better right.

At present, there are 45 domestic wells in the vicinity of the Bounds' property, with more to come when building and subdivision plans are approved. These wells are shallow, are allowed to pump up to 1 af/yr, and are within one mile of the river. Every gallon of water pumped from these 45 wells either intercepts groundwater baseflow to the river or pulls water from the river through increased infiltration. If they had water rights, all 45 wells would be junior to the Bounds' right. In essence, these wells allow junior appropriators to supersede a senior right. In 2006, Horace and Jo Bounds went to court and sued the state engineer and the state of New Mexico, arguing that the 1954 legislative statute was unconstitutional. On July 10, 2008, New Mexico Judge J.C. Robinson agreed. His decision held only in the counties where he has jurisdiction (Luna, Hidalgo, and Grant counties). This meant the required permitting was unconstitutional in part of the state and constitutional in the rest of the state, thus necessitating immediate action in the New Mexico State Supreme Court, even without an appeal from the defendant, the state engineer.

A closer look at the category of domestic wells indicates that they are hardly de minimis and that, in certain areas, they will have a dramatic impact on streams and rivers. In discussing the federal budget and efforts to curb profligate spending on defense items, the late US Senator Everett McKinley Dirksen once commented, "A million here and a million there, and pretty soon you're talking big money." The same is true with respect to domestic wells. Figure 14.8 shows the number of domestic wells drilled in a single year (1996) in each western state (NGWA 1996).

Furthermore, Fig. 14.9 shows the total number of household wells in each state as of 1996, the most recent year in which data are available. According to the National Ground Water Association, the average household well is drilled to a depth of 217 ft (NGWA 1996). Unfortunately, the only place one can usually secure water at that depth is near a stream. The cumulative effect of thousands of new wells coming on line each year, together with the recognition that the effects of these well depletions may not be apparent in the streamflow for decades, suggests a need for

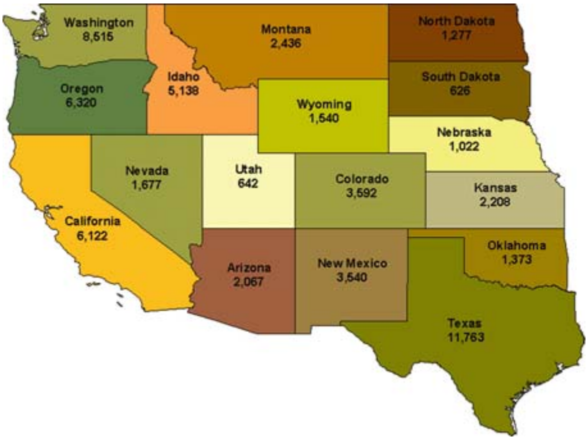

Fig. 14.8 Annual construction estimate for the number of new private household wells based on the most recent year for which data is available. (Source: Glennon and Maddock 1997)

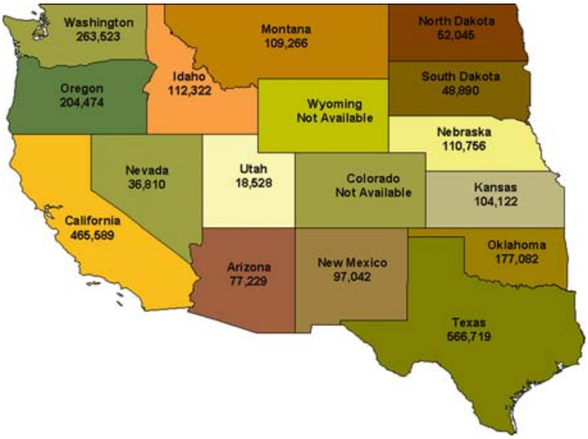

Fig. 14.9 Total number of household groundwater wells. (Source: Glennon and Maddock 1997)

immediate national attention to the problem. New Mexico has begun to do its part, and the rest of the prior appropriation states are likely to follow suit.

14.2.2.5 Water Resources Management in a Transboundary Basin: The Conchos

During drought, multiple reservoir systems often cannot fully satisfy demands from different users of the system, which might include irrigation districts, urban centers, and riparian biota. The issue is even more critical when international agreements and local policies require operators to fulfill specific requirements when using, storing, and distributing water. Using a Drought Frequency Index (DFI) developed by González and Valdés (2004, 2006) as a drought indicator, Cañon et al. (2008b) developed a hierarchical nonlinear optimal operation model of a system of five reservoirs and three irrigation districts in the Conchos River Basin of Mexico that minimizes water deficits and maximizes net benefits to users, including the expected deliveries to the US. The Conchos River flows entirely in Mexico, but because it is a tributary to the Rio Grande, its flows are affected by the international treaty of 1944 between the US and Mexico (Kim et al. 2002; Gastelum et al. 2009). The treaty specifies the minimum flows to be delivered by Mexico where the Conchos meets the Bravo/Grande River.

The DFI characterizes droughts according to their duration and intensity, using a probabilistic criterion that takes into account the persistence of extremely low precipitation values. Performances with and without the DFI show that including the DFI improves the reliability of the reservoirs to deliver water to users during periods of drought, especially at the first stages of prolonged dry conditions. This is reflected in an overall improvement of net benefits associated with crop production in the Mexican irrigation districts and in better deliveries downstream to the Rio Grande into the US in compliance with the international treaty of 1944. Figure 14.10 shows both the results of operating the Conchos systems utilizing an optimization

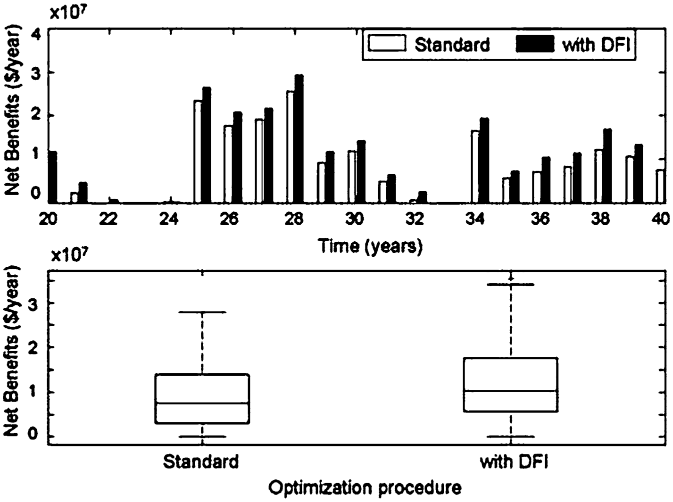

Fig. 14.10 Optimization results for the Conchos River Basin. (Source: Cañon et al. 2008b)

model directly and those obtained with the same optimization model but using the DFI as a trigger for rationing during severe droughts.

14.2.2.6 Climate Variability and Change in Semiarid Basins

According to the climate models participating in the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4 2007), projections for the US Southwest indicate that the region faces generalized temperature increases with the largest warming in the summer months and a likely decrease in precipitation. In the Colorado River Basin, the largest basin in the region, increasing evaporation losses due to higher temperatures will decrease river flows and increase drought conditions throughout the US Southwest (Christensen and Lettenmaier 2006; Hoerling and Eischeid 2007). In fact, the Southwest is one of the few regions in the world where there is consistent agreement among projections from 21 different coupled climate models that streamflow will decrease (Milly et al. 2005). Due to this decreasing flow, Barnett and Pierce (2008) estimate a 50% chance that live storage in Lakes Mead and Powell, the two largest reservoirs in the Colorado system, will be depleted by 2021.

In addition to future climate trends, the variability associated with projected El Niño Southern Oscillation (ENSO) conditions—an important driver for winter climate variability in the region—will contribute to the occurrence of extreme responses in the system. Dominguez et al. (2008) evaluated the ability of the IPCC coupled models to represent the climate of the Southwest and the future winter ENSO projections, particularly the seasonal precipitation variability. The Max Planck Institute's ECHAM5 and the United Kingdom's Met Office HadCM3—the two models that most accurately represent the seasonal precipitation over the region and, in addition, realistically represent ENSO variability—were selected using two different criteria: (1) similarity in precipitation and temperature estimates in historical and future data using a modification of the reliability ensemble analysis (REA) estimate (Giorgi and Mearns 2002), and (2) similarities in 500-millibar (mb) geopotential height patterns to determine the models' capability to capture monsoonal precipitation.[4]

While Dominguez et al. (2008) did not find statistically significant changes in ENSO future variability or in future winter teleconnections in the Southwest, they showed that the projected future aridity of the region will be dramatically amplified during La Niña years, which will be characterized by higher temperatures and lower precipitation than the projected trends (Fig. 14.11). These results have important implications for water managers in the Southwest who must prepare for more intense winter aridity associated with future ENSO conditions. Cañon et al.

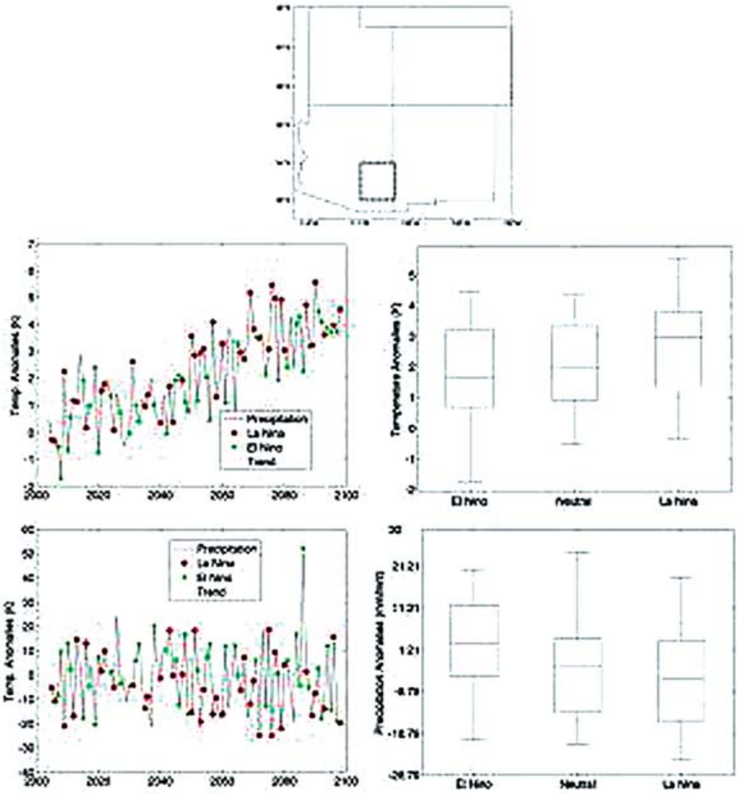

Fig. 14.11 Winter temperature (*left*) and precipitation (*right*) time series SRES A2 projections for the cell delineated in the top panel (–111_W to –109_W, 32_N to 34_N) using the MPI-ECHAM5 model. *Dots* correspond to La Niña years while squares correspond to El Niño. (Source: Cañon et al. 2008a)

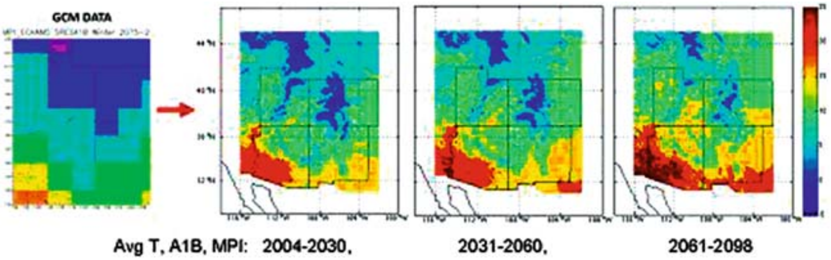

Fig. 14.12 Example of downscaled GCM projections for the US Southwest. The map to the *left* represents data at the GCM resolution. (Source: Cañon et al. 2008a) (See also Plate 16 on p. 345 in the color plate section)

(2008a) downscaled the GCM projections from a resolution of 192 km to a spatial resolution of 4 km, a scale that is meaningful for hydrologic modeling and decision-making purposes. Figure 14.12 shows an example of the spatial downscaling for the US Southwest in which the regional variability of temperature and precipitation is preserved.

Kang et al. (2009) developed a DSS for the Upper San Pedro Basin in Arizona to evaluate development scenarios for the region. The development of the DSS greatly benefited from contact with and involvement of the main stakeholders of the region, particularly the Upper San Pedro Partnership (USPP), a group composed of numerous public and private organizations and entities, including the city of Sierra Vista and Fort Huachuca in Arizona. Several development scenarios were evaluated and their results are presented for different reaches of the river (Fig. 14.13).

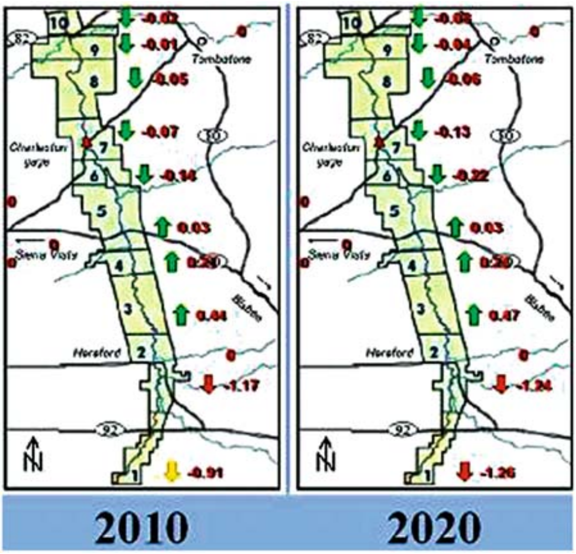

Fig. 14.13 DSS results for 2010 and 2020 development scenarios. *The arrows* indicate the direction of change in riparian groundwater levels; the *color of arrows* indicates the magnitude of change. *Red* represents greater change, and *green* represents smaller change. (Source: Kang et al. 2009)(See also Plate 17 on p. 346 in the color plate section)

To account for climate change, Serrat-Capdevila and Valdés (2008) coupled climate model projections with the groundwater budget of the San Pedro Basin for the Upper San Pedro DSS, building on the contributions of Serrat-Capdevila et al. (2007) and addressing some of its limitations. After reliability ensemble analysis and a bias correction to select the best climate models for the region, precipitation estimates at the basin scale were used to calculate recharge using a basin-wide lumped equation. An approach to infer changes in recharge due to evaporative losses and increases in the riparian corridor's evapotranspiration (ET) was developed. The findings of a detailed analysis of existing ET measurements allowed the calculation of riparian ET rates for the current century. Using the Penman–Monteith equation and meteorological projections of global climate models, it was possible to issue future projections of ET in warmer scenarios. The previous changes in recharge, temperature, and riparian ET are now being linked to the San Pedro DSS. The ultimate goal of the current work is to help set a new sustainable yield accounting for climate change impacts that go beyond the congressionally mandated attainment of sustainable yield of the regional aquifer by 2011.

14.3 Complexities of Water Management: A Recap

Management of surface water and groundwater in the US, particularly in the Southwest, is a complex task. One reason stems from the unequal treatment of water rights for surface water and groundwater. The fact that groundwater is still based on land ownership and is relatively inexpensive to obtain has made it possible for groundwater to be used for agriculture. Another reason is related to federally protected water rights: the Endangered Species Act and Native American water rights. Decisions to satisfy these water rights have been very controversial. For example, recent decisions by the Arizona Supreme Court giving priority to federally protected water rights are expected to become a major litigation issue in Arizona and other states.

Other factors that complicate management are the nonscientific basis for the treatment of groundwater's interaction with streamflows; the significant increase of water demand due to a population increase that is double the rate of the US as a whole; a severe drought on both sides of the US-Mexico border that has intensified the stress on water resources of the region; and similar growth on the Mexican side, creating tensions in water allocations that are regulated by international treaties in both the Colorado and Grande/Bravo basins. The only alternative to satisfy the growing water needs in the region would be a significant change in water use, from agricultural to municipal and industrial, but current political structure does not make this feasible in the short term.

Notes

1. Examples may be found at www.twdb.state.tx.us/wrpi/swp/previous.htm.
2. A laboratory within the US National Oceanic and Atmospheric Administration (NOAA).
3. US Supreme Court litigation is not cheap. In a previous Supreme Court case between New Mexico and Texas on the Pecos River, New Mexico—which lost the case—was assessed $195

million in settlement and compliance costs. Adding in court costs and consultant fees, the total far exceeded \$200 million. As great as that amount was, it pales in comparison to the cost that would have been incurred by the potential Rio Grande litigation.

4. Kim et al. (2006) studied the relationship between ENSO and annual precipitation in the Colorado basin.

Acknowledgments This research has been partially supported by the Center for Sustainability of Semi-Arid Hydrology and Riparian Areas (SAHRA) at the University of Arizona under the STC Program of the National Science Foundation, Agreement Number EAR-9876800. Julio Cañon, Aleix Serrat, Francina Dominguez, and Mary Black, all of SAHRA, have provided valuable comments and suggestions. All contributions are gratefully acknowledged.

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Chapter 15
Managing Water Amid Rapid Urbanization: Mexico's North Borderlands

Nicolás Pineda-Pablos and Alejandro Salazar-Adams

Abstract The arid and semiarid border cities of northern Mexico sit in a region of rapid industrial growth and development, but they face the challenge of supplying water to an ever-increasing number of people with ever-diminishing water supplies. A number of alternatives exist to meet this challenge: improvements in management efficiency, wastewater treatment and reuse, water transfers from agriculture, and seawater desalination. However, several factors within the current institutional framework, such as the turnover of water managers, the criteria used to design water rates, and the lack of effective sanctions for free riders, restrict the implementation of alternative solutions. In view of these constraints, a reform on water laws and a new institutional framework of urban water management are required to face the combination of water scarcity, economic growth, and the prospect of harsher and longer droughts in the near future.

Keywords Borderlands · Desert · Economic growth · Efficiency · Mexico

15.1 Cities in the Desert

In the years after World War II, American tourists used to cross the border into Mexico expecting a landscape of dusty towns where they could buy tequila, exotic food, and handcrafts. But with the emergence of manufacturing plants, called maquiladoras, and the North American Free Trade Agreement (NAFTA), exchanges between both sides of the border increased considerably; northern Mexico now resembles US border cities like San Diego and El Paso, with modern factories, hotels, fast-food restaurants, and shopping malls. Northern Mexico, especially the cities that border the US, has become an increasingly important economic zone that is often used to exemplify the impacts of free trade and foreign investment in Latin America (Marston et al. 2002; Fournier 2001). The border region includes

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G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
DOI 10.1007/978-90-481-2776-4_15,

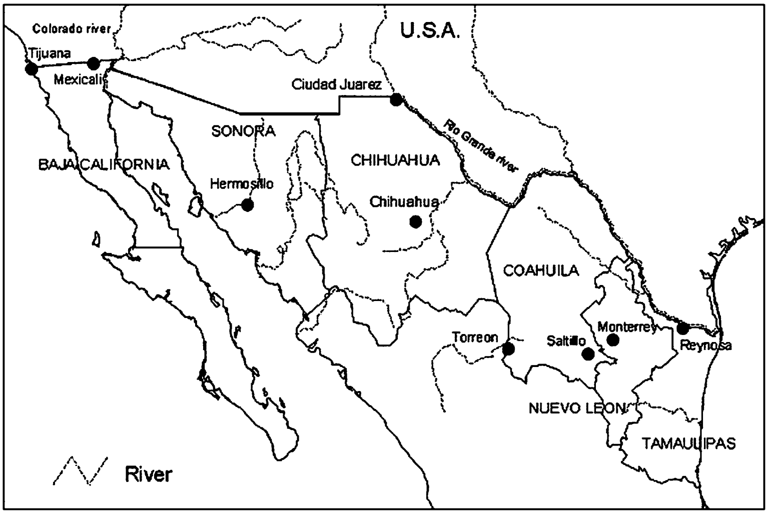

Fig. 15.1 Mexico's north borderlands

major cities with populations of more than one million people, such as Tijuana and Ciudad Juárez (Fig. 15.1). The region also is home to irrigated agricultural valleys, such as the Mexicali and the Lower Río Grande along the border or, farther south, the Yaqui and Mayo in Sonora, that produce a large percentage of Mexico's domestic and export crops. Also, the border towns of Nogales, Nuevo Laredo, and Reynosa became important commercial and industrial centers due to the maquiladoras during the last three decades of the twentieth century. In addition, the state capital cities of Mexicali, Hermosillo, Chihuahua, and Saltillo, each with a population of more than half a million people, and Monterrey, home to around 3.5 million residents, have become centers for business, services, universities, and technology even though they are located much farther from the border.

The problem posed by this rapid growth and development is that these cities are located in the fragile environment of the Sonoran and Chihuahuan deserts, where annual rainfall is low, summers are hot, and water is scarce.

In addition, climate projections call for warmer and stormier conditions. Thus, this region faces the challenge of maintaining the pace of economic growth and development with ever-diminishing water and the prospect of tougher and longer droughts in the near future. The region faces the problem of how to urbanize, industrialize, and develop an area where water is scarce and contested while ensuring sustainability. From an economic point of view, it is a problem of fixed and diminishing water supply and growing demand. From a sociological standpoint it might be seen as a matter of conflict and tension centered on a critical resource. Environmental concerns also exist regarding economic growth and development in the desert and the sustainability not only of cities, but also of sensitive natural habitats with rich flora and varied fauna. In addition, the region faces the geopolitical complication of being the political divide between the most powerful country and a developing nation where security, illegal drug trafficking, human smuggling, and international diplomacy are everyday issues. The questions are as follows: Can we have growth and development in the desert? What alternatives are being considered? Which constraints and hurdles are being addressed?

15.2 Growth and Water

The northern borderlands of Mexico include six states: Baja California, Sonora, Chihuahua, Coahuila, Nuevo Leon, and Tamaulipas. Socioeconomic and environmental factors converge to make water management a key issue for the development of this arid and semiarid region. While this area was grossly underpopulated up to the 1950s, the number of inhabitants has grown from 7.9 million in 1970 (a few years after the start of the maquildora programs) to 19 million in 2008, with an average annual growth of 2.3% (Table 15.1). Projections suggest that the population of the six border states will grow at an annual average rate of 1.1% within the next two decades—almost twice the estimated rate of the rest of Mexico (Conapo 2008).

Meanwhile, the population of the cities in these states will grow at a rate of 1.4% (Table 15.2). Thus, the population growth is unevenly distributed, as it tends to be concentrated in cities and is basically urban; the larger the city, the higher the

Table 15.1 Estimated country and state population for 2008, 2020, and 2030

	2008	2020	2030	Annual growth (%)
Mexico	106,682,518	115,762,289	120,928,075	0.6
Baja California	3,079,363	4,152,585	5,074,986	2.3
Coahuila	2,601,884	2,884,127	3,054,774	0.7
Chihuahua	3,359,934	3,673,626	3,838,176	0.6
Nuevo Leon	4,393,095	4,995,659	5,398,387	0.9
Sonora	2,487,608	2,716,953	2,841,311	0.6
Tamaulipas	3,154,947	3,565,224	3,824,091	0.9
North borderlands	19,076,831	21,988,174	24,031,725	1.1

Source: Conapo 2008

Table 15.2 Estimated population in cities with a population greater than 100,000

	2008	2020	2030	Annual growth (%)
Mexico	53,152,848	59,922,990	65,480,763	1.0
Baja California	2,376,332	3,397,442	4,164,884	2.6
Coahuila	1,729,662	1,970,286	2,248,647	1.2
Chihuahua	2,475,554	2,656,183	2,888,111	0.7
Nuevo Leon	3,598,717	4,038,820	4,472,779	1.0
Sonora	1,521,528	1,750,017	1,906,268	1.0
Tamaulipas	2,168,196	2,694,182	2,980,810	1.5
North borderlands	13,869,989	16,506,930	18,661,499	1.4

Source: Conapo 2008

growth rate. Currently, Tijuana, Ciudad Juarez, and Monterey each already have a population of more than one million people. Mexicali, Saltillo, Torreón, Chihuahua, Hermosillo, and Reynosa each have more than 500,000 residents. Thus, the population of the northern states is not only growing at a faster pace than the population in the rest of the country, but it is also agglomerating into the largest cities and with no local planning (Garza 2003).

Industry jobs are triggering this growth. Border states are now among the most industrialized in Mexico. The gross domestic product (GDP) of the region grew at an annual rate of 4.2% from 1993 to 2004, while that of the rest of the country trailed at 2.4%. Drawn to the region, American companies established maquiladoras across the border, taking advantage of cheap labor and tax incentives from the Mexican government through an industrialization plan for the region that started in 1965. In 1980, the maquiladora industry employed about 105,000 people. NAFTA was signed in 1994, and the number of jobs in the maquiladoras increased to 572,000 a year later. A little more than one million people were employed in the industry by 2000 (Turner 2006). A characteristic of this labor force, however, is that it tends to be young, female, low skilled, and low paid. For this reason, maquiladora jobs tend to be only a temporary option, highly mobile, and characterized by high rates of turnover (Kopinak 1996).

Rapid growth in the region also has had an impact on the patterns of urban settlement and the type of housing available. Border urban growth tends to be irregular, unplanned, and disorderly, expanding by means of shantytowns and squatter settlements made by people who build their houses with recycled materials in empty plots they do not legally own (Alegría and Ordoñez 2005). Beyond the tourist districts visited by American visitors, the landscape of Mexican border cities includes vibrant commercial zones; a varied mix of residential neighborhoods ranging from elite districts to the newly founded squatter settlements on the urban fringe; the old industrial districts; and the new industrial quarters of maquiladora parks (Arreola and Curtis 1993).

Ironically, this region, with such important economic development and high population growth, is also the most arid region in Mexico and North America. The average precipitation throughout the six states ranges from 202 to 463 mm a year (Conagua 2007a); the area next to the Colorado River has an average annual precipitation of only 50 mm (García 2003). The climate of the Río Grande states, on the eastern part of the border area, is warm, windy, and predominantly sunny. Although rain and humidity increase closer to the Gulf of Mexico, the area is also characterized as tropical and subtropical desert (Eaton and Anderson 1987). In contrast, the south and southeastern regions of Mexico (which are also the most underdeveloped) receive precipitation totaling 1,171–2,300 mm a year. The north borderlands are a drought-prone region that has faced significant and prolonged shortages in precipitation. The last drought began in the mid-1990s and ended in the mid-2000s (Esquivel 2002), and the region is expected to face a stronger and longer drought by the 2030s (Lenart 2007).

The climatic outlook is not very promising either. Borrowing from studies of the US Southwest, which has the same climate system as northern Mexico, global

Table 15.3 Water sources by city

Tijuana	Surface impoundment on the Tijuana River, augmented through an aqueduct from the Colorado River
Mexicali	Sources connected to the Colorado River
Hermosillo	Abelardo L. Rodriguez Dam and groundwater from La Victoria and La Sauceda wells
Ciudad Juárez	Groundwater (despite being next to the Rio Grande)
Monterrey	La Boca and El Cuchillo dams on the San Juan River, and the Cerro Prieto Reservoir
Reynosa:	Surface water from the Rio Grande, treated by two water treatment plants

Source: US Environmental Protection Agency 2001; Aranda et al. 1998; Salinas 2000

warming and its associated climate changes are likely to affect this region in a number of ways: warmer temperatures and more heat waves; more droughts yet more floods; reduced snow cover; increased strain on water resources; and an earlier spring with larger wildfires (Lenart 2007). The Intergovernmental Panel on Climate Change (IPCC) estimates an increase of 3–4°C in average annual temperatures in this region during this century (IPCC 2007).

The borderlands are home to some important water resources that likely will be affected by climate change (Table 15.3). Mexico and the US share parts of two major river basins: the Colorado River and the Rio Grande. Irrigation districts and cities located on both sides of the border have access to these rivers and have to share the water. Because population and economic activities have increased considerably, a great amount of stress is being put on the basin waters. To date, the amount of water drawn ranges from 72 to 86% of available water; an extraction of more than 40% is considered a constraining factor to development (Conagua 2006) (Table 15.4).

Most of the binational water is used in agriculture, while most cities along the border resort to pumping groundwater to satisfy the needs of residential and industrial users. For instance, Ciudad Juarez, despite its proximity to the Rio Grande, uses groundwater. However, most groundwater in the north borderlands of Mexico already is over-utilized. According to official data, 41 aquifers are over-exploited

Table 15.4 Water extraction by use (2006)

Region	Agricultural (%)	Municipal[a] (%)	Industrial[b] (%)	Thermoelectrical use (%)	Extraction Total (hm^3)
North borderlands	83.9	12.7	1.8	1.6	19,521.8
National	76.8	13.9	3.8	5.4	77,322.2

[a] Includes industries and services supplied by municipal water networks.
[b] Self-supplied industry, thermoelectrical plants excluded.
(hm^3): cubic hectometers $1 hm^3 = 1\ 000\ 000\ m^3$.
Source: Conagua 2007a; *Estadísticas del Agua en México*

Table 15.5 Characteristics of aquifers in northern Mexican states

Hydraulic region	Num. aquifers	Over-exploited	With saltwater intrusion	Withdrawal (hm^3)	Average recharge (hm^3)
Baja California	87	8	9	1,512	1,411
Noroeste	63	17	5	2,730	2,754
Río Bravo	96	16	0	4,123	5,218
Total	246	41	14	8,366	9,384

Source: Conagua 2004; *Estadísticas del Agua en México*

throughout the border states (Conagua 2007a). One reason for this is that the estimations of water pumped are generally based on the declarations of agricultural producers themselves who, in order to protect their own interests, tend to underreport the volume actually pumped. In addition, pollution is plaguing an increasing amount of groundwater, and saltwater intrusion has occurred in 14 aquifers (Table 15.5). Thus, demographic, environmental, and social factors as well as the climatic outlook increase the hydraulic stress of the region.

15.3 Facing the Water Challenge

In order to cope with the challenge posed by growth and water scarcity, urban water utilities in the northern borderlands made remarkable efforts during the 1990s to build the necessary infrastructure and have improved their efficiency and quality of service. Nevertheless, additional improvements are required. These include four main measures: (1) making water available for everybody; (2) increasing the efficiency of water management and reducing water loss; (3) treating and reusing wastewater in such a way as to minimize contamination; and, (4) finding additional sources of water for the cities if the goal of satisfying increasing growing demand is not met.

15.3.1 Service Coverage

The first challenge is service coverage—making water available to cover everyone's main needs, regardless of income or social condition. It is an equity challenge in a poverty-stricken country. In northern Mexico, an estimated 4.7% of the population in 2001 lacked water service to their homes, and 19.2% were not connected to the wastewater network (Saade 2005) (Table 15.6).

These proportions usually correspond to the poorest strata of the population and affect women, children, and rural populations most. Although these figures are lower than the national average, the challenge still exists and demands attention. The most dramatic case is Tijuana, where 24% of the population has no access to

Table 15.6 Coverage, average water supply, and water loss (2007)

City	Population	Population with no water service (%)	Water supply liters/person/day	Water loss (%)
Mexicali	698,357	1	330	14
Tijuana	1,315,773	6	222	19
Saltillo	583,604	4	181	67
Torreón	544,875	2	340	52
Chihuahua	716,781	6	440	47
Monterrey	3,459,121	1	276	30
Hermosillo	671,909	3	345	38
Reynosa	490,531	7	316	36

Source: Conagua 2007b; *Situación del Subsector de Agua Potable, Alcantarillado y Saneamiento*

wastewater services. The challenge is to provide both piped water and wastewater services to every household. Meeting this challenge, however, competes with the fight against poverty and unemployment, which are the main problems in Mexico, and with efforts to improve urban planning and social policies at the local level. The provision of water and wastewater services for everybody in northern Mexico is therefore the shared responsibility of the federal, local, and city governments and relies on the effectiveness of the programs that deal with these issues.

15.3.2 Reducing Water Loss

Increasing efficiency in water utilities—the second measure—is essential to water management in northern Mexico. A large proportion of water that is introduced into the system does not reach registered customers; it is lost due to old water pipe networks that lack maintenance and to leaks and clandestine taps (see Table 15.6). Therefore, reducing water loss means having additional water available for users without having to supply more water to the system. Efficient water management is the first priority for urban water utilities.

Four published indicators exist to measure the efficiency of Mexican water utilities: water loss (physical efficiency), water liters supplied per person (customer efficiency), proportion of free rider customers (commercial efficiency), and the ratio of employees per water connections (administrative efficiency). The proportion of water loss or physical efficiency is perhaps the most important for this analysis and corresponds to the percentage of water introduced to the network that actually reaches customers. The loss of water in northern Mexican cities ranges from 14% in Mexicali, which reflects very good management given the difficulty in achieving lower proportions, to a 67% water loss in Saltillo—that is, two-thirds of the water introduced into the network is lost and only 33% reaches customers. Because Saltillo has a water supply shortage, this is an indication of poor performance of water management, and it is also a potential source of additional water for future needs.

The number of water liters per person per day relates to the efficiency of water used by customers (see Table 15.6). This indicator varies from 181 L per person per day in Saltillo to 440 L per person per day in Chihuahua. The reduction in the amount of water used by customers might also provide additional amounts of water for future growth. The target number in Mexico is around the level of consumption reported by Saltillo. A matter of debate, however, is whether it is acceptable to ration Mexico's water service—reduce it to a certain number of hours per day, as is done in Saltillo—or whether it should be provided 24 hours a day, 365 days a year. The standard in northern Mexican cities is still to provide the service around the clock every day of the year. Only in exceptional cases have cities established rationing, usually as a temporary measure, to cope with water shortages. In these cases, customers usually install water tanks on the roofs of their houses to have a backup water supply.

The proportion of free riders—the number of customers who fail to pay for the services—reflects the financial management of water utilities and the behavior of customers. Commercial efficiency is the proportion of water bills actually paid by customers. The fact that many cities do not report this indicator highlights significant shortfalls in this regard. Among the cities that report the proportion of free riders is Chihuahua, where approximately 89% of the bills are paid and, on the other extreme, the city of Reynosa, which reports that only 64% of its customers pay. The proportion of unpaid bills points either to potential resources to finance service improvements or mismanagement of the customers' cadastres. In any case, this is an issue that should be addressed for the sake of the service and its financial sustainability.

The number of utility employees per every thousand water connections is a sign of administrative efficiency—whether the utility has just enough personnel or whether it is overstaffed. In this regard, Saltillo, which is managed by a public–private partnership, has the greatest administrative efficiency, reporting 2.2 workers for every 1,000 connections (Table 15.7). Conversely, Reynosa reports having 6.9 employees for every 1,000 customers—three times the personnel of Saltillo, making it the least administratively efficient of the four cities sampled.

Finally, global efficiency is obtained by multiplying the physical efficiency by the commercial efficiency. Hermosillo has the most globally efficient water utility, reporting 49%.[1] The city with the least efficient water utility of the four sampled is Reynosa, at 41% (Conagua 2007b). These efficiency levels clearly are still very low.

Although these statistics are not outstanding, they demonstrate an improvement with respect to the performance observed during the 1990s. Also, these figures exceed the national averages of 44% physical efficiency and 69% commercial efficiency (Conagua 2005). Thus, while the average global efficiency at the national level is 30%, the sample of statistics available for borderland cities shows levels that exceed 40%. Hence, perhaps because of the water scarcity and a more industrialized economy, north borderland water utilities show a greater efficiency than those in the

Table 15.7 Coverage and management efficiency in northern Mexico cities

City	Water supply coverage	Wastewater service coverage	Employees/1,000 customers	Physical efficiency %	Commercial efficiency %	Global efficiency %
Mexicali	99	93	n.a.	86	n.a	n.a.
Tijuana	94	78	3.9	81	n.a	n.a.
Saltillo	96	93	2.2	n.a.	n.a.	n.a.
Torreón	98	96	3.8	48	87	42
Chihuahua	94	89	4.3	53	89	47
Ciudad Juárez	n.a.	88	3.3	n.a.	n.a.	n.a.
Monterrey	99	98	3.7	70	n.a.	n.a.
Hermosillo	97	94	4.1	62	80	49
Reynosa	93	89	6.9	64	64	41

Source: Conagua 2007b; *Situación del Subsector de Agua Potable, Alcantarillado y Saneamiento.*

central and southern regions of Mexico. However, there is still significant room to improve water management efficiency.

15.3.3 Wastewater

The third goal is to increase the proportion of wastewater treatment, recycling, and reuse. Nuevo Leon, the state with the best figures in water treatment at the turn of the twenty-first century, treats 100% of its wastewater, which is then reused for crop production (Table 15.8). Baja California follows with 83%. Of the other four states, only Sonora is below the national average; it treats less than one-third of its wastewater. Although the proportion of wastewater treated in the region is greater than the national average, a significant volume is still polluting rivers instead of being used to irrigate parks and gardens or for other public uses. If water becomes scarcer and more valuable, wastewater treatment will become an important source of additional water for desert cities.

Table 15.8 Wastewater treatment (L/sec)

	Generated	Collected	Treated	%
Baja California	6,058	5,349	4,442	83.0
Chihuahua	12,320	11,001	6,242	56.7
Coahuila	7,020	6,416	2,753	42.9
Nuevo León	9,650	9,178	11,102	100.0
Sonora	9,929	8,450	2,581	30.5
Tamaulipas	8,715	7,155	3,444	48.1
Mexico	242,099	205,838	74,388	36.1

Source: Conagua 2007b; *Situación del Subsector de Agua Potable, Alcantarillado y Saneamiento.*

15.3.4 Finding Additional Sources of Water

The fourth challenge is to increase the supply of water for cities. Many city authorities traditionally consider the first option for meeting demand, focusing only on the supply side of water management while ignoring the management of water demand. Usually this translates to the transfer of water from other basins and the construction of aqueducts to bring additional water to the city. For instance, the technological solution for the provision of water in Tijuana and Monterrey was the construction of aqueducts and canals for interbasin water transfers. Tijuana relies on an aqueduct built in the 1970s that brings water from the Colorado River Delta and feeds most of the city's water needs. Since the mid-1990s, Monterrey has pumped water from the El Cuchillo Dam, located in the neighboring state of Tamaulipas, thus solving its own serious supply problems. The aqueducts and canals were made possible by expropriations and, in the case of Monterrey, faced great opposition from Tamaulipas. There is a growing awareness of the problems this solution presents: it disrupts the water cycle, discriminates against users downriver, and most of all, does not fit well into the approach of integral and sustainable water management (Carabias and Landa 2005).

Other alternatives that have been considered to increase water supply are the transfer of water rights from agriculture to urban use and the desalination of seawater (see Chapters 6 and 19). The latter has already been applied in Baja California, where a desalination plant was built in 1970 (Correa 2007). Attempts were made at the turn of the century to install a desalination plant in Hermosillo, but those efforts were blocked (Pineda-Pablos 2007). The other alternative, water transfers from agriculture, face a number of legal hurdles as well as opposition from the crop-exporting farmers of the region. The Mexican Law of National Waters of 1992 did not anticipate the transfers from agriculture into urban use. These transfers were only made by presidential order and usually amid much opposition and conflict. The law was modified in 2004 to introduce, among many other measures, "title transmission" (Diario Oficial de la Federación 2004). Now, with the democratization of the country and the diminished powers of the president, these transfers involve difficult negotiations and are still subject to authorization by water authorities. With this new legal base and the support of national and state water authorities, Hermosillo signed a deal in 2005 with local farmers to acquire agriculture water rights. This acquisition has provided a new source of water for the city and has helped meet the peak urban demand in the summertime without resorting to rationing. This operation taps a new water supply source for the city in the future, but new negotiations and costly deals are necessary to make water transfers from agriculture available for cities.

15.4 Limitations of the Institutional Framework

Despite having made significant improvements, north borderland cities have not fully applied alternatives to meet the urban demand for water because they face obstacles embedded in the current institutional arrangement that might prevent their implementation. Institutions constrain and orient human behavior and activities. The aim of an institution is to reduce uncertainty by establishing procedures and structures for human interaction. The concept of an institution is not reduced to formal rules and laws and comprises "rules-in-use" (Ostrom et al. 1993; Ostrom 2007; Schneier-Madanes and de Gouvello 2003). Therefore, in order to analyze the situation and outlook of water management in arid and semiarid northern Mexico, it is necessary to review some existing rules and incentives for administering this resource. Three major institutional constraints prevent water utilities from implementing long-term planning and achieving self-sustainability: (1) the high turnover of urban water managers and the failure of long-term planning, (2) the criteria used to design and approve water rates, and (3) limitations for the enforcement of sanctions against free riders.

Water supply services in Mexico were transferred from the federal government to state and municipal governments in the 1980s, and the appointment of water managers has been linked to the politics of local governments ever since (Pineda-Pablos 2008). Because there is no reelection in Mexico and municipal governments change every three years, water managers are removed at least every time a new government administration takes office, if not more frequently (Table 15.9). In Sonora, for example, water managers remain in office for an average of 26 months (Pineda-Pablos 2008). In addition, the selection of people for these positions is based on political and electoral criteria rather than on technical competence.

Due to the high turnover, neither continuity in the management of urban water resources nor effective planning exists. Nevertheless, the principle of no reelection is considered a remarkable outcome of the Mexican Revolution and a protection against dictatorial governments or caciques (local overlords).[2] The elimination of this principle must be reconsidered because it has perverse effects on municipal planning and administration. The expectation is that, as free and competitive elections provide a means for penalizing bad governments, the no reelection rule will be eliminated in the future.

Among the likely solutions for this lack of management continuity are the introduction of a merit-based civil service in the water sector and the establishment of regulatory boards. Some efforts have been made in the state water laws to introduce permanence and incentives for a civil service career in water management, but they are weak and insufficient. Governors and water authorities are reluctant to renounce

Table 15.9 Water managers' turnover

City	Number of managers 1990–2006	Average years in office
Tijuana	5	3.2
Saltillo	5	3.2
Chihuahua	7	2.3
Monterrey	8	2
Hermosillo	10	1.6

Source: Data collected directly by the authors their vested appointed powers. Thus, more citizen pressure is required to attain the necessary legal reforms and their due enforcement to really establish a career and civil service in the sector.

Another likely solution is the creation of state technical regulatory boards that might participate in the appointment of utility managers, help build institutional capacities, and generally oversee and assess the operation of water services. Although this idea has been around for some time, it also faces the same problem as civil service: it implies a diminishing power of governors and authorities. Therefore, it depends on further political and citizen development.

So far, the only solution devised and put into practice to overcome the lack of continuity in the management of urban water utilities is to promote the participation of the private sector in the operation of urban water services (Diario Oficial 1992; Conagua 1989, 1990). Responding to this call, the private sector has increased its participation, mainly in the construction and operation of wastewater treatment plants and aqueducts (Conagua 2003). Nevertheless, in the operation of water services, private participation has been rather low. Only four cities (out of more than 130 cities with more than 50,000 inhabitants) have contracted with private management. Among the few cases of private participation are the cities of Aguascalientes, Cancún, and, in part, Mexico City, which introduced private participation in 1994 and 1995. In 2001, Saltillo entered into a joint venture with Aguas de Barcelona to manage the water utility.

The primary reasons for this overall lack of participation are the higher stakes in service quality stipulated in operation contracts, the inexperience of local companies, the greater financial risks posed by free-riding customers, and the political overtones posed by the operation and management of water utilities (Conagua 1990; Saade 2005; Schneier-Madanes 2005). A characteristic of private participation in Mexico is that contracts have been assigned only to large construction corporations, such as ICA (Ingenieros Civiles Asociados) or Tribasa (Triturados Basálticos), in conjunction with multinational companies like Aguas de Barcelona or Lyonnaise des Eaux. These corporations take great care in the billing and collection of water user payments without investing significantly in improving infrastructure or customer service. On the other hand, community associations or small-sized local firms have not been invited and have not had the same opportunity to participate in water investment ventures. Thus, the most widely used strategy for the management of urban water in Mexico is that of public management provided by the local government. For this reason, it is necessary to institute procedures that encourage administration and planning that are not limited by the short life spans of local governments.

Another rule or procedure of the institutional framework that causes adverse effects on water management is the criteria used to approve the water rates. The federal government allowed water utilities to approve their own water rates according to their financial needs, thus avoiding the interference of political bodies such as the state congresses or municipal councils, which often care more about the electoral impact of raising water rates (Conagua 1989). In this regard, during the 1990s, 23 states passed legal reforms granting utilities the authority to set their own water rates (Alcántara Palma 1996). However, in response to several lawsuits, the Supreme Court decided in 2001 that rates must be passed by the state congresses. As a result, the approval of water rates has been given back to the state congresses, where the criteria for the design and approval of rates are becoming more political than technical. The revision and increase of water rates has become a subject debated among congress members of different parties with an eye to obtaining electoral gains, so the rates are not increased or they fall short of the level required for the sustainable operation of the service and the total recovery of costs. Therefore, the court's decision is counter to the financial health of water utilities and inhibits their development.

In addition to the constraints imposed on pricing policy, payment is not enforced in most states. Most utilities issue bills, but almost half of the users in some cities do not pay them on time or stop paying without facing penalties. The basis for this lack of enforcement is an interpretation of Article 121 of the Ley General de Salud (General Health Law), which establishes that water providers will not be able to withhold the supply of water and sewage services of inhabited buildings except in cases determined by the general applicable laws (Diario Oficial 1984). Most utilities do not cut off the service because of this rule. In some cases, the sewage outlet is only restricted as a substitute for a sanction, or the water quantity provided is reduced. This situation has created commercial efficiency problems because a large number of users have not paid for the service, damaging the financial sustainability of water utilities.

15.5 Rationality in Water Management

The cities of Mexico's north borderlands face the challenge of providing water to an ever-increasing population that demands greater levels of consumption with limited resources. This challenge will only grow if projections of more severe drought play out in the future. These cities have to increase their efficiency and their levels of wastewater treatment and resort to the transfer of water rights from the agricultural sector to the urban and industrial sectors. To a lesser extent, the cities of Baja California and Sonora, located near the coast, can also resort to seawater desalination in order to satisfy demand.

The task of revising and adjusting the institutional framework must be accomplished to remove obstacles and to correct behaviors that are or can be harmful and may affect the performance of water management. The frequent turnover of managers in Mexican water utilities is directly tied to the periodic change of local governments; the life span of these administrations—and therefore the time directors of water utilities remain in office—is three years at most due to a no reelection principle. In order to strengthen the technical capacity of water utilities, it is necessary to institute new forms of management that allow more effective planning for this sector and more consistent decision making. Without this institutional change, medium and long-term urban development planning cannot occur, and water management will remain stuck in the vicious cycle of lack of resources, low management capacity, and cheap, low-quality services. In addition, the most important change perhaps is in the financial realm and has to do with achieving self-sufficiency of water services.

The price of water is the key mechanism to introduce rationality into water management; however, the Supreme Court has decided that the state congresses are to determine or approve the rates instead of water utilities themselves. As a result, water prices do not tend to promote the total recovery of costs and self-sufficiency. It is therefore necessary to find mechanisms that compensate for the political and electoral criteria of congress members and emphasize the requirements of self-sufficiency and sustainability of water utilities.

Users must pay for the service if the price mechanism is to work as a rationalizing element that encourages water conservation. Nevertheless, water providers in Mexico cannot discontinue the service to residential users who do not pay on time due to an interpretation of the General Health Law. As a result, between one-third and one-half of the users do not pay their water bills on time.

In order to strengthen and encourage sustainability and efficiency in water management in Mexico, it will be necessary to debate and revise the current institutional framework and General Health Law so the northern Mexico borderlands can meet water demands in the future.

Notes

1. We have information to estimate this indicator for only four cities, and all of them fall in the range of 41–49%.
2. The Mexican Revolution started in 1910 with the purpose of overthrowing Porfirio Díaz, who had been in power for more than 30 years. When the revolution succeeded, a new constitution was written in 1917 prohibiting the reelection not only of the president, but of any authority at any level in the country, to prevent power perpetuation.

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Chapter 16
Forecasting Streamflows in the San Juan River Basin in Argentina

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Abstract San Juan province, located in western Argentina, presents great climate variability with arid characteristics. Mean annual rainfall averages less than 100 mm for the whole province, and snowmelt in the Andean upper basin provides the San Juan River Basin with seasonal streamflow during summer, the period of highest water demand for irrigation. Traditional streamflow forecasts for the San Juan River are based on statistical regression models that are strongly dependent on values of snowpack in winter months (July, August, and September) and streamflow values in the spring months. However, producing forecasts for San Juan River summer streamflow using the Multivariate El Niño Southern Oscillation Index (MEI) data in the preceding June of the water year as an explicative variable can improve reservoir operating system performance for irrigation. To demonstrate this, climate predictors such as the MEI were used to forecast San Juan River streamflows to provide predictability at a six-month lead time. A backpropagation neural model, based on coupled data of snowpack and a climate predictor during the winter period, proved successful in forecasting San Juan River flows during the following summer period.

Keywords Arid basin · Backpropagation neural model · Forecast · Irrigation · Streamflow

16.1 Long-Lead Streamflow Forecasting

Wide swaths of land are dedicated to agriculture in Argentina's dry San Juan province, where regional incomes are closely tied to crop yields and a water supply, particularly for irrigation during summer. Arid and semiarid regions like San Juan comprise more than one-third of the Earth's surface and are mainly located between

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G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
DOI 10.1007/978-90-481-2776-4_16, © Springer Science+Business Media B.V. 2010

the tropics where atmospheric circulation generates dry winds. Only 11% of the soils suitable for agriculture may be cultivated without irrigation. The remaining 89% need conditioning and management to be productive (FAO 2007). About 40% of the world population—2.4 billion inhabitants—live in dry and semiarid regions. South America has wide expanses of arid and semiarid regions, yet it supplies 26% of the available water resources in the world and is home to only 6% of the world's population. On a national scale, the South American countries are very heterogeneous in relation to weather, soil characteristics, and resources distribution, in particular water distribution. Seventy percent of Argentina may be considered arid or semiarid, but only 30% of its population—approximately 12 million people—live in those areas. As a comparison, 18% of the land in Brazil is arid or semiarid, but the population in those areas totals about 20 million inhabitants, or 10% of the country's total.

Only 12% of the total superficial water resources in Argentina (2,600 m^3/sec) are located in arid and semiarid regions. Agricultural activities are mainly performed under irrigation. The irrigated areas comprise about 1.1 million hectares (ha) in the arid and semiarid regions (INDEC 2002), which lie mainly in the west, near the Andes Mountains and in Patagonia. In the central-west area (Mendoza and San Juan provinces), irrigated agriculture is significant to local economies.

Like many other rivers with snow melting regimes, the San Juan River Basin (SJRB) in Argentina presents seasonality in the value of its flows, with peaks in the summer months of December, January, and February, when water is necessary for irrigation. Developing forecasting streamflow models plays an important role in optimizing water resources management, especially for summertime irrigation. Long-lead streamflow forecasting methods based on forecasts of El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) climate signals for the Northwest Pacific basins (Hamlet et al. 2002; Piechota and Dracup 1996) and similar studies in the South Pacific in Argentina and Chile (Masiokas et al. 2006) provide a basis to produce forecasts for San Juan River summer streamflow using the Multivariate ENSO Index (MEI) data in the preceding June of the water year as an explicative variable.

A comparison was made of the application of an Artificial Neural Network (ANN) model for the prediction of the San Juan River summer flows based on winter MEI and snowpack data (predictability at a six-month lead time), with a traditional statistical method based on the multivariate regression of flows dependent on values of snowpack in winter months (July, August, and September) and streamflow data in spring months (predictability at a three-month lead time).

ANNs mimic the way the human brain learns from examples through a process that involves finding an optimal set of weights for the interconnections between nodes (neurons) of the network, arranged in groups called layers. A network usually has three layers: the input layer—a set of data, in this case winter snowpack and MEI; the hidden layer where data are processed; and the output layer where the results, in this case summer streamflows, for given inputs are produced. Learning (or training) in ANNs is defined as self-adjustment of the weights as a response to changes in the information environment, a transfer function that controls the generation of the output of a neuron, and learning laws that describe how the adjustment of the weights are made during training (Haykin 1999; Hertz et al. 1991).

16.2 The San Juan River Basin

San Juan province is located in the central-west region of Argentina. The general climate is marked by scarce rainfall and important thermal amplitudes caused by the massive Andes Mountains. The high peaks of the Main Andes prevent the arrival of the humid winds from the Pacific Ocean. Eighty percent of the province is covered by three major north–south trending mountain ranges: the Andes (Cordillera Principal on the border with Chile and the Cordillera Frontal), the Argentine Precordillera, and the Sierras Pampeanas. The Cordillera Frontal is the major Andean topographic feature in the region and rises to an elevation of more than 6,000 m. The Precordillera mountain belt, which stretches nearly 400 km and measures roughly 80 km wide, is a thrust-and-fold belt separated from the Cordillera Frontal by a north–south piggyback basin: the Calingasta Valley of the San Juan River. To the east, the Precordillera is flanked by the Bermejo foreland basin that separates the Precordillera thrust-belt from the Sierras Pampeanas, a structural province characterized by ranges uplifted above moderate to highly dipping, mostly west-verging reverse faults that root deeply into the Precambrian basement rocks (Ramos et al. 2002).

The main weather data (1940–2007) for San Juan province are the following (SMN 2007):

Mean maximum temperature: 26°C
Mean minimum temperature: 9°C
Mean relative humidity: 54%
Mean annual precipitation: 93 mm
Effective heliophany: 7.9 h
Winds: southeast–northeast and Zonda (warm and dry, which blows from the west).

The San Juan River crosses the southwest region of the province in the northwest–southeast direction and belongs to the Colorado River hydrographic system. The upper part of the basin runs along the Calingasta Valley, from the union of the Castaño and Los Patos rivers, in the Andes. In the middle basin, at Valley Ullum, its channel widens and the Ullum and Ignacio de la Rosa dams irrigate the area surrounding the city of San Juan.

16.2.1 San Juan River Hydrology

The snowpack in the central Andes (30–37° S) is the primary source of streamflow in the San Juan River and in all of central-western Argentina. A statistical hydrologic characterization of the San Juan River was performed on the basis of monthly flow data (EVARSA 2007) (see Figs. 16.2 and 16.3).

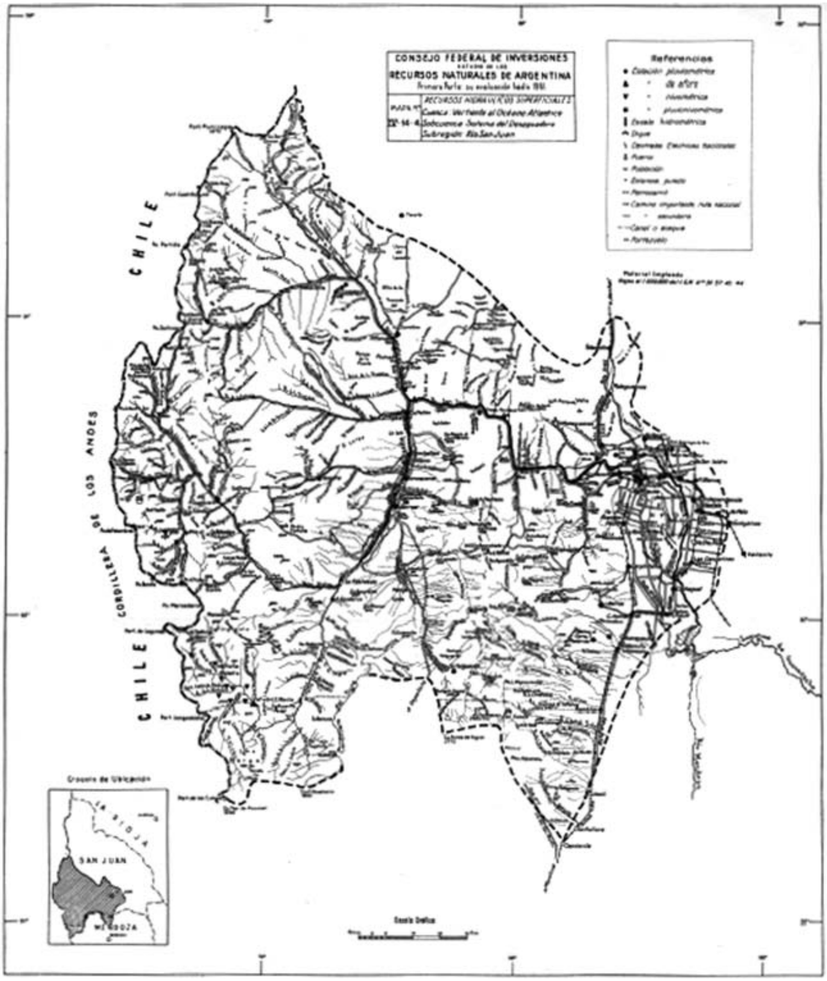

Fig. 16.1 San Juan River Basin, Argentina

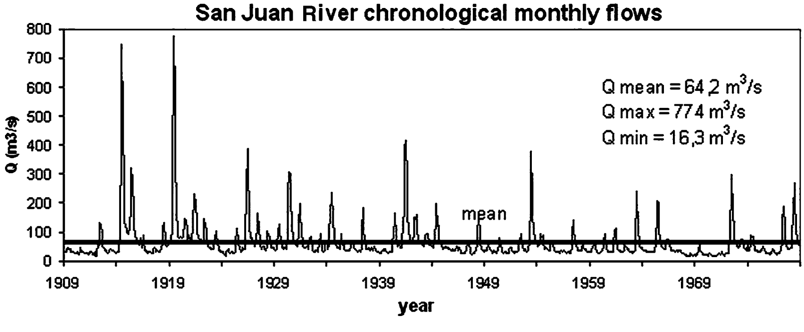

Fig. 16.2 Flow frequency curve, San Juan River (1909–1979)

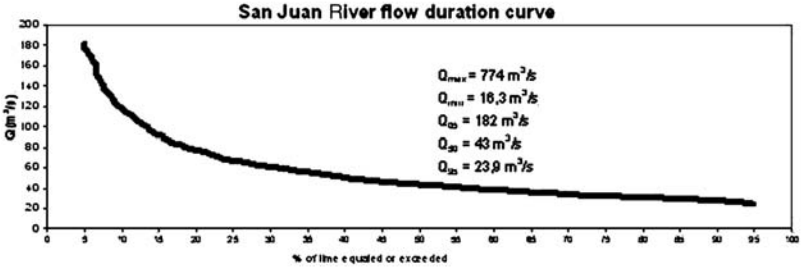

Fig. 16.3 Flow duration curve, San Juan River (1909–1979)

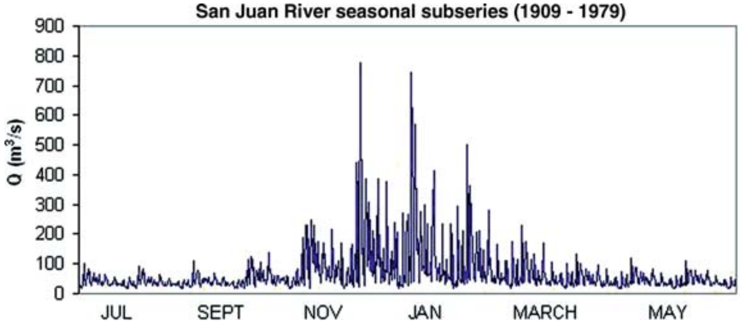

Fig. 16.4 Seasonal subseries curve, San Juan River (1909–1979)

The seasonal subseries shows the seasonality of the monthly flow series for the 1909–1979 study period; the snowpack series of data were irregular after 1979 (Fig. 16.4).

The box plot curve is also useful, as it provides a visualization of the maximum, minimum, and average San Juan River flows for each monthly flow of the year throughout the study period (Fig. 16.5).

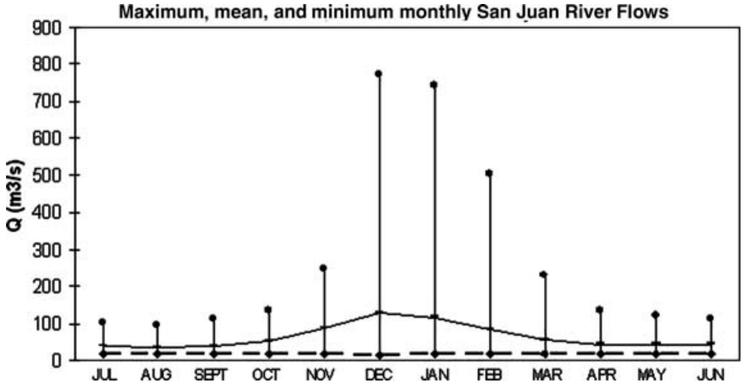

Fig. 16.5 Box plot, San Juan River flows (1909–1979)

This analysis reveals the following highlights about the San Juan River hydrology (data EVARSA 2007):

- The series shows a seasonal regime with great dispersion of flow values in the summer months: December, January, and February (Fig. 16.5).
- Extraordinary floods above 700 m^3/sec occurred in January 1915 and December 1920.
- The series is stationary for the period 1950–1979, but not for 1909–1979. Autocorrelation studies were developed to assess stationarity (Box and Jenkins 1976).
- The Hurst phenomenon (existence of long-term memory) was verified with a ratio $H = 0742$ (Hurst et al. 1965; Bras et al. 1993).

16.2.2 The Importance of Irrigation to the Economy

The main use of the San Juan River water is for irrigating crops in the Tulum-Ullum-Zonda Valley in the SJRB region. A wide irrigation system supplies most of the cultivated lands in 14 departmentos (local jurisdictions) that surround San Juan City (Ullum, Zonda, Pocito, 9 de Julio, Rivadavia, Sarmiento, Albardon, Angaco, San Martín, 25 de Mayo, Caucete, Rawson, Chimbas, and Santa Lucía) (Fig. 16.6). The population of this area, which since colonial times has been the most representative economic region in the province, totals 408,548 inhabitants (INDEC 2001), or three-fourths of the total population of the province.

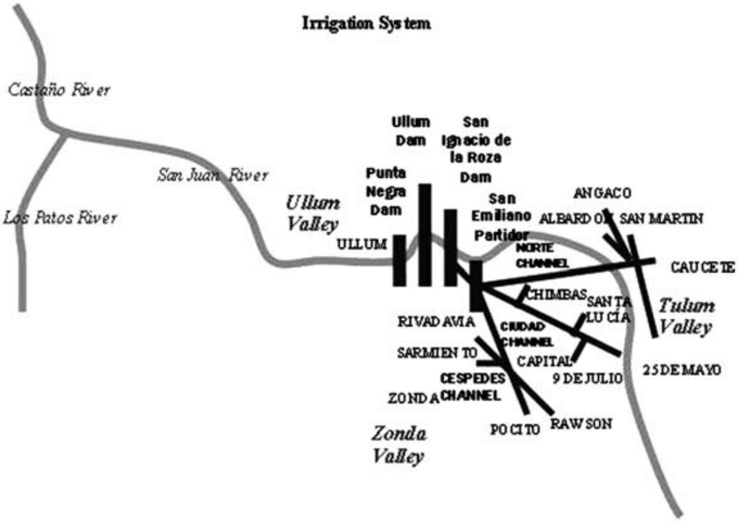

Fig. 16.6 Irrigation system in SJRB. Adapted from a study of the National Institute of Agriculture Technology: *Agro-ecological Characterization of Sown Valleys in San Juan and its Relationship with Saline Problems*

The SJRB irrigated zone represents the most important agricultural area in the province. Thousands of hectares are sown, primarily with traditional species. The SJRB has 89,103 ha of cultivated land, up 28% since 2002. The irrigation systems cover 83% of these lands; the remaining 17% are sown by means of rain-fed agriculture (Departamento de Hidráulica de San Juan 2007).

Spread over 50,388 ha—89.9% of which are irrigated lands (45,258 ha)—grapes are the main crop grown in the SJRB region, and they represent 50% of the sown area there. The second main crop is olive, with 15,488 ha cultivated (7,832 ha are irrigated), making up 8.8% of the cultivated area of the region. Other crops of importance are vegetables, forage, and fruits. They represent 8.4%, 4.8%, and 3% of the sown area, respectively; the importance of irrigation to each crop is 99.9%, 82.6%, and 91.8% (Departamento de Hidráulica de San Juan 2007). In addition, 73% of forest and 53.3% of forage crops are cultivated using irrigation systems.

SJRB agricultural production is important to the province's economic activity; in 2007, SJRB agriculture accounted for 9% of the Provincial Gross Geographical Product (PGGP) and 71% of the agricultural sector's production in PGGP (Krause et al. 2000; Dirección Nacional de Programación Económica Regional 2002).

16.3 Data Used

In developing a long-lead streamflow forecasting model, three distinct types of data were required to perform the proposed forecasting analysis: streamflow records in the SJRB; snowpack measures in the Andean upper basin; and values of MEI, the main index integrator of the ocean–atmosphere system that explains global climate change at an interannual range in the Pacific Ocean. The following data were used:

- Series of snowpack thickness in the SJRB at the Laguna de La Arena, Rondadero, and General San Martin stations for 1950–1978 were considered (EVARSA 2007). Some periods of interruptions in the data occurred after 1979.
- Series of values of MEI data for 1950–1978 (NASA 2007). The data have only been available since 1950.
- The use of data in two currently active stations was considered among active flow stations in the San Juan River: one was located at km 101 and the other at km 47.3. The streamflow data presented here come from the latter station; therefore, forecasts are related to this station, and data considered were the average monthly flows in the San Juan River, station km 47.3, for the years 1909–1979 (EVARSA 2007).

16.4 Model Performance Criteria

To compare performance of the ANNs model with multiple regression (MR) models usually used in the region, the following three commonly used measures have been applied to assess the model's goodness of fit:

16.4.1 Mean of the Squared Errors (MSE)

MSE is the average of the squares of the differences between the predicted and actual values. It is a reasonably good measure of performance, though it could be argued that it overemphasizes the importance of larger errors. Many modeling procedures directly minimize the MSE.

$$MSE = \frac{1}{N} \sum\nolimits_{p=1}^{N} (Q_p - Q_m)^2 \tag{16.1}$$

16.4.2 Mean of the Absolute Percentage Errors (MAE)

MAE is similar to the MSE, but it uses absolute values instead of squaring. This measure is more intuitive (i.e., the "average error").

$$MAE = \frac{1}{N} [\sum\nolimits_{p=1}^{N} \left| Q_p - Q_m \right| / Q_m \tag{16.2}$$

16.4.3 Correlation Coefficient (R)

R measures the explanation of the variance of the values.

$$R = \frac{\sum\limits_{p=1}^{N} (Q_p - \overline{Q_p}).(Q_m - \overline{Q_m})}{\sqrt{\sum\limits_{p=1}^{N} (Q_p - \overline{Q_p})^2.(Q_m - \overline{Q_m})^2}} \tag{16.3}$$

where

Q_p is the predicted value
Q_m is the observed value
N is the total number of values
$\overline{Q_p}$ is the mean of the predicted values
$\overline{Q_m}$ is the mean of the observed values

16.5 Forecasts with Multiple Regression Model

Multiple regression or multivariate analysis is a statistical method that allows researchers to establish a mathematical relationship between a set of independent variables $X_1, X_2 \ldots X_k$ (covariates or factors) and a dependent variable Y.

In this case, the objective of the regression model (predictive model) is an equation that allows researchers to "predict" the values of Y (San Juan summer streamflows) once the values of $X_1, X_2 \ldots X_p$ are known. In the traditional method used until now, independent variables $X_1, X_2 \ldots X_p$ were snowpack in the precedent winter season and spring streamflows. In this case, the lead time for the prediction of summer flows is three months.

The multiple linear regression model with p predictive variables and based on n observations is given by

$$Y_i = \beta_o + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots \ldots \beta_p X_{pi} \tag{16.4}$$

where i = 1.2,. . .. n.

It can be considered as a system of linear equations of the following form:

$$\begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ . \\ y_n \end{bmatrix} = \begin{bmatrix} 1 \; x_{11} \; x_{12} \; . \; . \; x_{1p} \\ 1 \; x_{21} \; x_{22} \; . \; . \; x_{2p} \\ . \quad . \quad . \; . \; . \; . \\ .. \quad . \quad . \; . \; . \; . \\ . \quad . \quad . \; . \; . \; . \\ 1 \; x_{n1} \; x_{n2} \; . \; . \; x_{np} \end{bmatrix} \begin{bmatrix} \beta_0 \\ \beta_1 \\ . \\ . \\ . \\ \beta_p \end{bmatrix} \tag{16.5}$$

That is, **Y** = **X ß**, where **Y** is an n dimensional column vector, **X** is a matrix n × p′, with p′ = p +1, and **ß** is the p′ dimension vector of regression coefficients to be estimated.

According to the precedent methodology, regression models were developed using summer streamflows in the SJRB as a dependent variable and earlier winter snowpack thickness in the upper basin as an independent variable with a calibration period of 1950–1967. Afterwards, predictions of summer streamflows were made on the basis of data of winter snowpack for the prediction period 1968–1978; above mentioned MSE, MAE, and R measures of model goodness of fit were calculated.

Two additional multiple regression models also were tested: one used snowpack thickness in the upper basin and MEI in the previous winter season as independent variable values, and the other also included the values of streamflows in the previous spring (Table 16.1).

The best performing model was that which was based on the thickness of snowpack and MEI (Fig. 16.7), thus confirming that flows of the previous spring did not add important information, given their high correlation coefficient with the values of snowpack.

Table 16.1 Runoff forecasts with multiple regression models

MR Model Variables	MSE	R	MAE
Snowpack	36.0	0.915	38.2
Snowpack, MEI	35.4	0.920	37.7
Snowpack, MEI, Qt-1	35.5	0.919	38.4

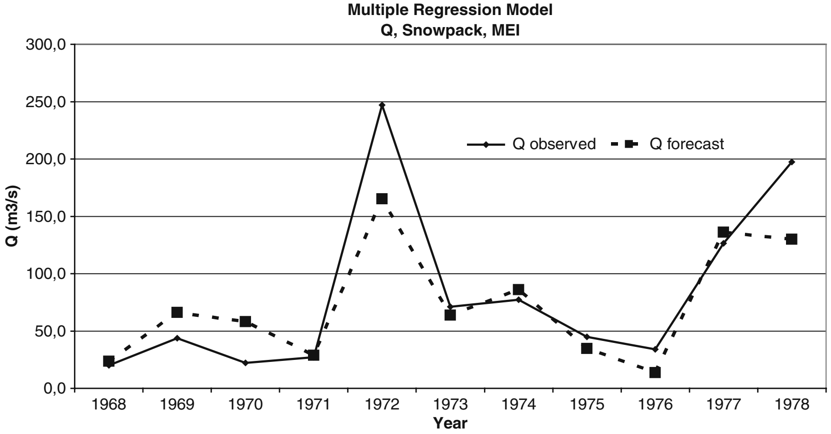

Fig. 16.7 Multiple Q—MEI

16.6 Neural Network Model

ANNs have been applied successfully in hydrological forecasting as a modeling technique for nonlinear systems. Their major characteristic is that they are capable of approximating nonlinear functions (ASCE 2000). An ANN is a network of weighted, additive values with nonlinear transfer functions. The original perceptron model consisted of three layers: (1) an input layer that worked as a "retina" that distributed inputs to the second (hidden) layer, (2) "association units" that combined the inputs with weights and triggered a threshold step function that fed to the output layer, and (3) the output layer, which combined the values and gave the results. As the use of a step function made the network difficult to train, a multilayer neural network with nonlinear but differentiable transfer functions that avoided the pitfalls of the original perceptron's step functions was proposed and proved to be successful (Rumelhart et al. 1986).

The multilayer perceptron feed forward network with three layers was considered for the analysis. This network has an input layer (on the left) with two neurons, one hidden layer (in the middle) with three neurons, and an output layer (on the right) with one neuron. There is one neuron in the input layer for each predictor variable. In this case, winter snowpack in the upper SJRB and MEI data were introduced in the input layer and summer streamflow values were produced in the output layer (Fig. 16.8).

The input quantities (snowpack and MEI data) were fed to input nodes Ni1 and Ni2, which in turn passed them in the forward direction into the hidden layer nodes after multiplying input quantities by a weight (w_{ji}). Arriving at a neuron $\mathrm{N_h}$ in the hidden layer, the value from each input neuron is multiplied by a weight (w_{ji}), and the resulting weighted values are added together, associated with a bias, producing a combined value u_j. The weighted sum (u_j) is fed into a transfer function, σ,

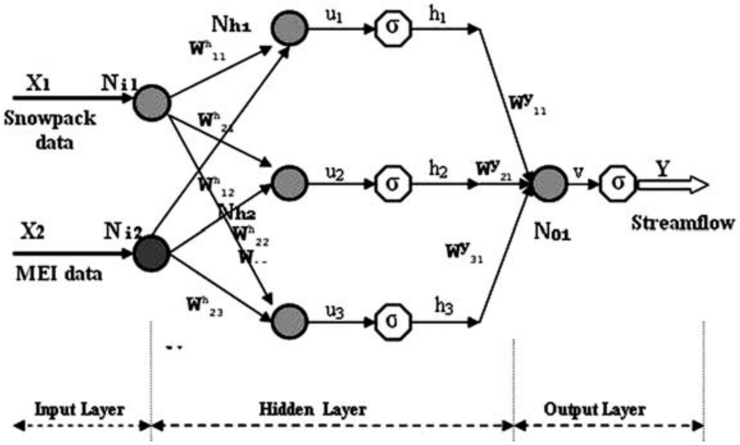

Fig. 16.8 Artificial Neural Perceptron Network with three layers

which outputs a value h_j. The outputs from the hidden layer are distributed to the output layer.

Arriving at a neuron N_o in the output layer, the value from each hidden layer neuron is multiplied by a weight (w_{kj}), and the resulting weighted values are added together producing a combined value v_j. The weighted sum (v_j) is fed into a transfer function, σ, which outputs a value y_k. The Y values (streamflows) are the outputs of the network.

Before its application, the network was first trained, whereby the target output at each output was compared with the network output, and the difference or error was minimized by adjusting the weights and biases through the training algorithm. In the current study, the backpropagation training technique was used to make sure the training was done. The least mean square error method, along with the generalized delta rule, was used to optimize the network weights. The gradient descent method, with the chain rule of the derivative, was employed to modify the network weights (Haykin 1999).

Different configurations of neural networks were tested, including three, four, five, and six neurons as the number of neurons in the hidden layer; sigmoid and hyperbolic activation functions with their parameters; and different values for the error in the learning (training) step.

The prediction model was operated with a forecasting horizon of six months, with input from snowpack and MEI winter data. The model was run on FANN (Fast Artificial Neural Network), a library designed to create fully connected neural networks (FANN 2007).

The application of neural networks to the problem of forecasting flows consisted of two parts. In the first part, ANN was trained with triad data entries in the values of X1 and X2 (snowpack and MEI, respectively), and the respective summer flows Y1, with a training period of 1950–1967. In the second part the forecast resulted in

Table 16.2 Runoff forecasts with Artificial Neural Perceptron Network with three layers

ANN Model Variables	MSE	R	MAE
Snowpack	34.9	0.916	31.3
Snowpack, MEI	33.9	0.916	31.0

the values of summer flows Y1 as output based on the input values X1 and X2 for the 1968–1978 period.

The results for this model, with a six-month horizon, are shown in Table 16.2 using snowpack as an explicative variable in one case and snowpack and MEI data in another (Fig. 16.9).

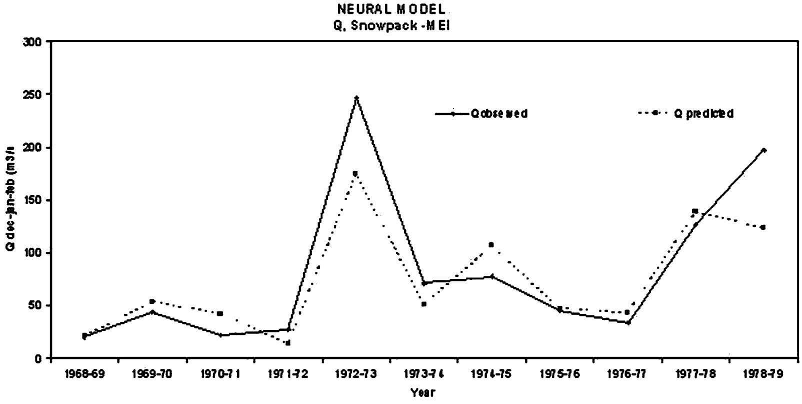

Fig. 16.9 Artificial Neural Perceptron Network with three layers (ANN Model Q—MEI)

16.6.1 Comparison between the ANN and MR Models

To compare the performance of the ANN model with the MR model, MSE, MAE, and R were estimated for each model run (Table 16.3). Even though the results are not very satisfactory in either model (moderate values of R), the forecasts made by the neural network model are better than those produced by the MR model, and a better performance of the ANN model can be considered on the basis of the MSE and MAE values.

Table 16.3 Comparison of runoff forecasts between MR and ANN models

Model variables	MODEL	MSE	R	MAE
Snowpack	MR	36.0	0.915	38.2
	ANN	*34.9*	*0.916*	*31.3*
Snowpack,	MR	35.4	0.920	37.7
MEI	*ANN*	*33.9*	*0.916*	*31.0*

16.7 Benefits of Improved Forecasts

The contribution of SJRB's agricultural production in the PGGP is estimated at about $200 million per year as a mean value for 1993–2007 (CFI 2007). Important benefits, therefore, could be achieved by optimizing water resources management—and thus increasing productivity—through better forecasts of water availability.

Nevertheless, it should be taken into account that the economic value of forecast information for the operation of scarce water resource systems can be difficult to assess (Yeh et al. 1982). One reason for this is that existing water management decision processes, which have evolved in the absence of new kinds of forecast information, may have no pathway to incorporate improved forecasts. Therefore, in assessing the economic value of improved forecasts, the decision processes themselves must be examined and strongly supported by the water resources management authorities of the province.

The analysis indicates that the pattern of ANNs is comparable to traditional methods of summer streamflow prediction for the snowmelting regime in the western basins of Argentina. ANN information processing systems that are composed of nonlinear and densely interconnected processing elements, or neurons, are flexible; they can therefore incorporate different types of data and capture nonlinear behavior in the time series studied.

Because a significant relationship exists between ENSO signals and summer streamflow in the arid SJRB, ENSO-based long-range forecasting of SJRB streamflow may be considered important to hydrologists and water resource planners for the maintenance of a diverse ecosystem and for operation of irrigation water resource systems in that region of Argentina.

Although the ANN model was run only in the SJRB case, the results presented are encouraging. For the SJRB and other basins in western Argentina, the results demonstrate a high potential for the application of neural networks in useful, long-lead streamflow forecasting roughly two months earlier than current forecasts that rely on winter snowpack and spring streamflow data. The resulting increase in forecast lead time facilitates improvements in irrigation system operating performance, especially in years of expected important changes in average flows, based on MEI data during the winter months.

Acknowledgments The authors are grateful to Lic. Silvana Curcio for providing invaluable research assistance. They also gratefully acknowledge the collaboration of engineers Juan Pablo Braña and Andrés Rocchia (Facultad de Ingeniería-UBA) for helping run the Fast Artificial Neural Network (FANN) program. All errors are ours.

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Chapter 17
Arsenic and Water Quality Challenges in South America

Alejo Pérez-Carrera and Alicia Fernández Cirelli

Abstract The presence of arsenic in soils and water is a threat to public health and agricultural activities because this toxic element poses contamination risks to plants, animals, and humans. Central Argentina (northern area of department of Union, province of Córdoba) and northern Chile, (El Loa, II Region de Antofagasta) are two of the areas most affected in the world and are representative of the arsenic contamination problem in arid and semiarid regions in South America. In both areas, arsenic levels in water are above the World Health Organization guidelines for human consumption (10 μg/L), and health effects in both sites have different manifestations. Nevertheless, the general trend in epidemiological studies is to find a relationship between chronic arsenic ingestion and cancer occurrence. Scarce data are available in most regions of South America. Environmental monitoring is not a common practice in many countries and should be implemented to verify that current environmental quality norms are met, carry out baseline studies to obtain the necessary data for developing contamination control tools, and estimate the population's exposure to arsenic. Conveying information to the population about arsenic water contamination and possible solutions is central to overcoming the problem.

Keywords Argentina · Arsenic · Chile · Groundwater · Surface water

17.1 An Introduction to Arsenic Contamination

Arsenic contamination of drinking water is a problem that demands special attention because it poses health risks to large numbers of people. Arsenic is a ubiquitous element found in the atmosphere, soils and rocks, natural waters, and organisms. Its transport in the environment is due to a combination of natural processes, such as weathering reactions, biological activity, and volcanic emissions, and anthropogenic activities. These activities include mining, the combustion of fossil fuels, and the use

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G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
DOI 10.1007/978-90-481-2776-4_17,

of arsenic in pesticides, as a wood preservative, and as an additive to animal feed. In water, under natural conditions, the greatest range and the highest concentrations of arsenic are found in groundwater. This is due to the strong influence of water-rock interactions and the greater tendency for physical and geochemical conditions in aquifers to be favorable for arsenic mobilization and accumulation (Smedley and Kinniburg 2002).

The main species of arsenic found in the environment are arsenic (III) and arsenic (V) oxyacids. In many environments, arsenic (V) is often deprotonated as an arsenic (V) or arsenate anion; in contrast, the arsenic (III) oxyacid remains in its neutral form as arsenite. Arsenates, arsenate anions, and neutral arsenite constitute the main targets for field analysis (Cullen and Reimer 1989). In contaminated soils, inorganic arsenates are the predominant species. In general, arsenate and other arsenic (V) species are immobilized on available surfaces, usually on or in iron oxides. Although arsenic (V) compounds that are associated with iron oxides are considered a low risk, bacterial and other environmental activities can readily convert them back into more bioavailable and toxic forms of arsenic (Miretzky and Fernández Cirelli, in press).

Groundwater and soil also may contain organoarsenic species: monomethylarsenic acid, dimethylarsenic acid, trimethylarsine oxide, and trimethyl arsine. In general, organoarsenic compounds are less toxic than their corresponding oxyacids. Although usually found in lower concentrations in freshwater lakes, methylated arsenic can comprise up to 60% of the total arsenic. Arsenic sulfur species also exist that are found in mineralized and reducing environments, both in sediment and in solution. Although all of these species are not as common or currently believed to be as toxic as arsenic oxyacids, they constitute a sizable fraction of the naturally occurring arsenic and should be a target of field measurements (Matschullat 2000; Adriano 2001; Mandal and Suzuki 2002; Smedley and Kinniburg 2002).

An important key to understanding the environmental risk from arsenic is bioavailability—the measure of the amount of arsenic that can be absorbed by a living organism. Bioavailability is likely to play a strong role in future environmental regulatory decisions because it is more representative of health risks than total arsenic concentration.

Arsenic occurs naturally in sedimentary and other aquifers, which are used in many developing areas as sources of drinking water. Additionally, natural arsenic is often found in thermal and mineral waters, which reach the Earth's surface either by natural discharge in springs or geothermal exploitation. Groundwater from large areas in the world contains high arsenic levels due to geogenic sources. It is, therefore, an issue of primary environmental concern. The presence of arsenic limits the use of these resources for human consumption and agriculture and hinders the economic and social development of the affected regions. The use of high-arsenic groundwater in agriculture is related to food security because a low relative permeability of the soils, deficient drainage, and/or intense evapotranspiration may lead to arsenic absorption by the crops through irrigation (Fundación Chile 1993; Muñoz et al. 2002). In addition, arsenic is transferred to milk or other

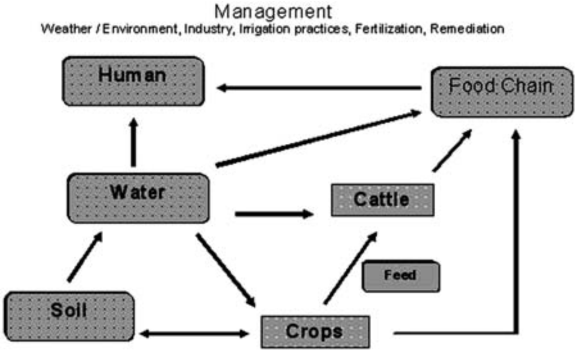

Fig. 17.1 A general overview of the arsenic cycle in the agriculture environment. (Source: adapted from Adriano 2001)

tissues through livestock ingestion, mainly from drinking water (Pérez-Carrera and Fernández Cirelli 2005; Pérez-Carrera et al. 2009).

A general overview of the arsenic cycle, including arsenic entrance into the food chain, is shown in Fig. 17.1.

At least four million inhabitants of South America drink water with high arsenic levels (>10 μg/L). In 2001, when the maximum allowed level of arsenic in drinking water was 50 μg/L, the affected population in Argentina totaled about one million inhabitants (3% of the total population). Now that this limit has been lowered to 10 μg/L in accordance with World Health Organization (WHO) recommendations, 2.5 million inhabitants (7% of the total population) are estimated to be exposed (WHO 2003).

The presence of arsenic in Argentina and Chile was discovered long ago. With the recent detection of arsenic in groundwater in other South American countries such as Bolivia, Peru, Brazil, Ecuador, and Colombia, it is now considered a regional problem (Sancha and Castro de Esparza 2001). Health effects from chronic arsenic ingestion were described early in the twentieth century in Bell Ville (Córdoba, Argentina) and later in Antofagasta (Chile). In Argentina's Córdoba Province, HACRE (Hidroarsenicismo Crónico Regional Endémico, or Chronic Endemic Regional Hydroarsenism) was recognized as an endemic disease caused by arsenic contamination of drinking water and characterized by skin lesions that may lead to a particular type of skin cancer (Astolfi et al. 1981). In the Second Region of Chile (El Loa, II Region de Antofagasta), adverse health effects have been noted in rural populations since 1962 and include arsenic-induced skin lesions and bladder and lung cancer (Smith et al. 1998; Smith et al. 2000; Romero et al. 2003).

Although the extent of the arsenic problem globally has not been determined, these two locations are among the areas known to be the most affected in the world. The two sites also are representative of the arsenic contamination problem in arid and semiarid regions; the area in Chile is characteristic of arid, high-elevation regions and mining activities, while Córdoba Province in Argentina represents extended plains in the transition area from subhumid to semiarid climatic conditions, with agriculture as the main economic activity.

Small and rural communities are exposed to high risk because they cannot benefit from large economies of scale to finance water treatment processes. Rural communities in developing countries have less developed local institutions, and transaction costs are higher. For these reasons, developing countries need to identify and implement strategies for managing arsenic problems, mainly in rural areas. The principal element of effective environmental control is information and accurate and complete monitoring. Without adequate information, it is impossible to mitigate environmental degradation and health effects through suitable policies.

17.2 The Extent of the Arsenic Problem in Two Study Areas

17.2.1 Argentina

Covering an area of about 1×10^6 km^2, the Chaco Pampean Plain of central Argentina constitutes one of the largest regions known to have high concentrations of arsenic in the groundwater (1 million km^2) and includes Córdoba and 12 other provinces. The concentrations found range from <1 to 5,300 μg/L (Nicolli et al. 1985, 1989, 1997; Pinedo and Zigarán 1998; Cabrera et al. 2001; Smedley and Kinniburg 2002; Farías et al. 2003; González et al. 2003; Pérez-Carrera and Fernández Cirelli 2004, 2005). The area of study is the department[1] of Union, located in the southeast of Córdoba Province, between longitude 62°33′ and 62°57′ west and latitude 32°12′ and 32°50′ south (Fig. 17.2).

With an area of 165,321 km^2, Córdoba makes up 4.48% of Argentina and is the fifth largest province in the country. The study area, measuring 11,182 km^2, was chosen because of the high arsenic content found in the groundwater there and because the region is one of the main dairy producers in the country.

The climate is semiarid to subhumid. The average annual temperature is 16.5°C, with average highs occurring in January (23.9°C) and average lows in July (9.4°C). Summer temperatures can exceed 40°C, whereas winter has seen the mercury plunge below –10°C. The average annual rainfall is around 800 mm with a significant seasonal distribution; 75% of the total rainfall occurs during the summer and the remainder during the winter. This distribution, together with the variability of the monthly and annual means, explains an appreciable difference with respect to the nonseasonal rainfall pattern of the humid pampa, the local name for the plains.

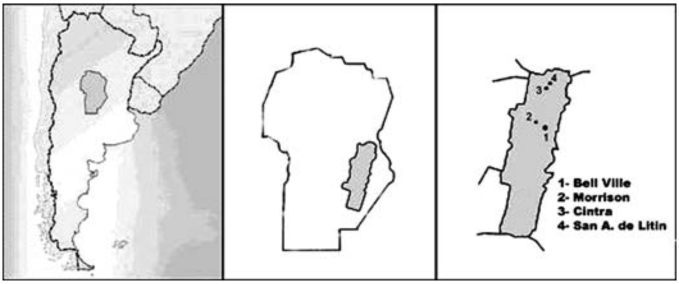

Fig. 17.2 Study area 1. Department of Union, province of Córdoba, Argentina

The population in the department of Union (100,250 inhabitants) is mainly urban (78.5%); 12% live in rural localities (< 2,000 inhabitants), and nearly 10%—9,477 inhabitants—live in dispersed rural localities. This isolated rural population is exposed to higher arsenic levels (0.05–4.5 mg/L). The distribution of arsenic concentration in groundwater in this area does not respond to a defined pattern. Therefore it is almost impossible to assess the distribution of population at risk with regard to arsenic concentration (Pérez-Carrera 2006). Heads of households in the department represent more than 30% of the total population; 22% correspond to the economically active population. Agriculture is the main source of income (INDEC 2001).

17.2.1.1 Superficial and Subterranean Hydrology

The most important watercourse is the Tercero-Carcarañá (or Calamochita) River, which flows through the study area from west to east. Its tributaries are the Saladillo and Mojarras streams from the south and the Tortugas—which runs through canals for much of its course—from the north. The Tercero River is considered a fresh water river. Its electrical conductivity (EC) ranges from 560 microSiemens per centimeter (μS cm^{-1}) in the city of Bell Ville to 5,000 μS cm^{-1} where it joins the Saladillo. The river receives a larger amount of salts from the Tortugas (EC: 19,000 μS cm^{-1}) and Santa Lucía streams (EC: 17,800 μS cm^{-1}).

In general, the underground runoff flows in the same direction as surface water (from west to east), but it is influenced by the north–south orientation of the tectonic structures. The phreatic level (shallow groundwater) is located at depths of 3–15 m and is characterized by brackish water with generally high saline and sulphate concentrations. A low relative soil permeability, deficient drainage, and intense evapotranspiration in the whole region contribute notably to the high saline and arsenic concentrations in shallow groundwater (Nicolli et al. 1985). The Pampeano aquifer—between 20 and 60 m deep, with sandy layers that are 7–10 m thick—provides limited and brackish water. This aquifer is used for agricultural activities and is often used for drinking water by isolated rural populations.

The Puelches aquifer, situated at the base of this aquifer, is between 80 and 120 m deep and constitutes the highest quality groundwater source in the area. Though brackish, the water is considered more acceptable for human and livestock consumption. A confined aquifer between 300 and 350 m deep has also been described in the same area, with good production, but in general with high salinity (Nicolli et al. 1985).

17.2.1.2 Arsenic in Water Sources

Arsenic problems in groundwater are caused by a combination of the element's high toxicity at relatively low concentrations and its mobility in water, both in the pH ranges of most groundwater and over a wide range of redox (reduction–oxidation reaction) conditions. Under oxidizing conditions at a high pH, arsenic is less strongly bonded to iron oxides than at lower pH values (Dzombak and

Morel 1990; Smedley et al. 2002). Hence, mobilization is enhanced and, under these oxidizing and high pH conditions, arsenic contamination may be a widespread phenomenon, as it is in the Chaco–Pampean aquifers (Smedley et al. 2002). An analysis of arsenic contamination in the Chaco–Pampean Plain is shown in Table 17.1.

Table 17.1 Areas contaminated with arsenic (As) in the Chaco–Pampean Plain, Argentina

Province	Population	Affected departments[1]	[As] in water (median, μg/L)*	Affected area (km^2)	Population at risk	% of province population
Chaco	1,007,850	Almirante Brown	90	49,481	333,863	33
		Comandante Fernandez				
		Fray J.S.M. de Oro				
		General Belgrano				
		Independencia	63	49,481	333,863	33
		Libertad	53			
		Libertador General	120			
		San Martín	60			
		Maipú	850			
		Mayor Luis J.	280			
		Fontana	55			
		Presidencia de La	260			
		Plaza	270			
		Sargento Cabral	150			
		Tapenagá	500			
La Pampa	313,810	Catriló	100	45,758	140,450	45
		Chalileo	180			
		Chapaleufú	130			
		Conhelo	100			
		Guatraché	100			
		Hucal	80			
		Maracó	60			
		Quemú Quemú	100			
		Rancul	100			
		Toay	150			
		Trenel	120			
Córdoba	3,199,362	General Roca	280	58,543	458,155	14.5
		Marcos Juárez	120			
		Pte. Roque Sáenz	51			
		Peña	80			
		San Justo	51			
		Sobremonte	203			
		Unión				
Jujuy	634,722	Santa Bárbara	54	14,559	105,410	17
		El Carmen	141			
		Susque	207			

Table 17.1 (continued)

Province	Population	Affected departments[1]	[As] in water (median, μg/L)*	Affected area (km^2)	Population at risk	% of province population
Salta	1,122,260	Rivadavia	330	73,532	82,841	7.5
		Anta	160			
		Los Andes	170			
Tucumán	1,387,220	Graneros	62	1,678	13,063	1
Santiago del Estero	823,817	Banda	200	17,625	195,431	24
		Copo	88.5			
Santa Fe	3,135,972	Belgrano	140	92,125	828,877	26.5
		Castellanos	110			
		General López	60			
		Iriondo	80			
		Las Colonias	100			
		9 de Julio	110			
		San Cristóbal	130			
		San Jerónimo	140			
		San Martín	120			
		Vera	100			

*micrograms per liter
Source: CONAPRIS-MSAL 2006

The shallow aquifer in the study area (Unión, Córdoba, Argentina) is made of Quaternary sediments, primarily of loessic origin. The aquifer contains high concentrations of arsenic associated with these loess and loess-like sediments, and fluoride, which is derived from volcanic glass with fluorapatite. The most important mechanism of release of fluoride is an ion exchange facilitated by the presence of calcium carbonate and clays in the aquifer (Cabrera et al. 2001; Farías et al. 2003).

The presence of arsenic in groundwater, due to its origin, is related in Argentina to the presence of fluoride (Nicolli 1985). Therefore, the presence of this element is a confirmation of the origin of arsenic in the study area. Fluoride content in shallow groundwater shows a strong positive correlation with arsenic (minimum: 0.6 mg/L; maximum: 10 mg/L; average: 3.2 mg/L; standard deviation (SD): 2.7). The same correlation, but with lower values and variation, is observed for groundwater from a depth of 80–120 m, where fluoride concentrations range from 0.3 to 1.5 mg/L; average: 0.5 mg/L; SD: 0.3 (Table 17.2).

Although the presence of arsenic in groundwater is always associated with fluoride in the Pampean region in all the study cases performed, there is no evidence of synergetic or antagonistic effects on human health. Both elements have different, well-documented health impacts (Pinedo and Zigarán 1998; Cáceres 1999;

Table 17.2 Physical–chemical parameters, major ions, and trace elements in water samples from livestock farms (phreatic level, deep wells, and superficial water) in Córdoba Province (Argentina)

	Phreatic level				Deep wells				
Parameter	Maximum	Minimum	Average	SD	Maximum	Minimum	Average	SD	Superficial N=1
pH	9.2	7.4	8.3	0.7	9	7.3	7.7	0.5	8.8
Conductivity*	7420	1154	3439	1742	6060	1210	2300	1224	305
TDS**	4985	1208	2625	1004	3995	904	1521	726	321
Hardness**	584	9.5	141	146	607	69	228	161	62
Chlorides **	1398	9	445	430	1195	137	307	241	43
Bicarbonates**	1589	436	847	298	818	89	274	157	106
Sulphates**	1104	105	444	293	1212	216	408	298	93
Sodium**	1520	358	778	323	1153	203	431	204	52
Potassium**	47.7	11.8	24.6	9.6	36.6	10.6	16.9	5.7	4.9
Calcium**	144.5	1.9	29.6	34.3	203.5	16.4	55.4	47.9	17.6
Magnesium**	54.2	1.2	16.4	15.2	75.8	6.8	21.7	16	4.4
Arsenic**	4.5	0.08	1.1	1.4	0.2	<0.01 ***	0.04	0.04	<0.01***
Fluoride **	10	0.6	3.2	2.7	1.5	0.3	0.5	0.3	0.4

SD: Standard Deviation
TSD: Total Dissolved Solids
* μS cm^{-1} (microSiemen*s* per centimeter)
** mg/L
*** Detection limit

Ferreccio et al. 2000; Hopenhayn-Rich et al. 2000; Sancha and Castro de Esparza 2001; Smith et al. 2000).

In the study area, arsenic concentrations in shallow groundwater (3–15 m deep) are highly variable (minimum: 0.08 mg/L; maximum: 4.5 mg/L; average: 1.1 mg/L; SD: 1.4). In deep wells, concentrations range from <0.01 (detection limit) to 0.2 mg/L; average: 0.04 mg/L; SD: 0.04 (see Table 17.2).

In Argentina, the limit for human drinking water recently has been reduced from 0.05 to 0.01 mg/L (AAC 2007), as dictated by WHO guidelines. All water samples from shallow groundwater show arsenic levels above the established limit for human consumption. On the other hand, arsenic content in water from the Tercero River is less than the detection limit (<0.01 mg/L), while the fluoride content is up to 0.4 mg/L. Superficial water is therefore considered a safer source for human supply than groundwater in terms of arsenic concentrations (Pérez-Carrera and Fernández Cirelli 2004).

Environmental monitoring has not been implemented in this area, and mitigation practices are not applied. Nevertheless, once the problem was detected at the beginning of the twentieth century, the drinking water supply for urban localities shifted from groundwater to superficial water that lacked arsenic. For isolated rural populations and livestock, groundwater remains the main source of drinking water. In the department of Unión, 78% of the population (78,735 inhabitants) is urban with easy access to safe drinking water, 12% (12,035 inhabitants) live in small towns, and the remaining 10% (9,477 people) comprise isolated rural populations that are exposed to higher arsenic concentrations because the inhabitants drink groundwater. In the city of Bell Ville, the department seat, superficial water from the Tercero River is used as drinking water because groundwater in this area—mainly shallow—has high arsenic concentrations. Major ions in groundwater are within the ranges accepted for livestock consumption both in shallow and deep groundwater wells, with the exception of sulphates, which have been measured at concentrations that surpass recommended levels (200 mg/L). In the phreatic level (3–15 m depth), both arsenic and fluoride concentrations exceed the recommended guidelines for livestock drinking water.

Agriculture is one of the most important economic activities of Córdoba. Cereal and oleaginous crops are concentrated in the center and south of the province. The main crops are wheat, corn, soybean, and sunflower. This province, with its rich grasslands and alfalfa, provides Argentina with 35% of the nation's milk; the study area ranks third largest in dairy production in Córdoba. Arsenic concentrations in soils and sediments in the area have been reported to range from 2.1 to 8.2 mg/kg, with a mean rate of 4.2 mg/kg (Pérez-Carrera 2006). These levels are less than the values reported for polluted soils (US EPA 1985).

Pérez-Carrera and Fernández Cirelli (2005) began studies on the incidence of high arsenic in drinking water in livestock health and arsenic transfer to milk and other cow tissues. The results obtained in 50 middle-sized dairy farms show very low arsenic content in milk. The biotransference factor is of the same order of magnitude as that reported in Comarca Lagunera, Mexico (biotransfer factor: 10^{-4}–10^{-5}), and consuming it does not represent a health risk (Rosas et al. 1999). Despite this, arsenic levels in cow livers and kidneys are in accordance with those reported in other areas affected by arsenic in water (from 10 to 70 ng g^{-1}) (Kramer et al. 1983; Vos et al. 1987; Jorhem et al. 1991; Salisbury et al. 1991; Kluge-Berges et al. 1992; López-Alonso et al. 2000; Pérez-Carrera 2006). The determined levels do not present a health risk, although the animals have been exposed to high-arsenic drinking water.

17.2.2 Chile

The Chilean study area is situated in the province of El Loa in the Antofagasta region (Fig. 17.3), where the population is grouped in villages of generally fewer than 1,000 inhabitants. Antofagasta is an arid/semiarid area well known for the anomalous amount of arsenic found in its water, soil, and rocks. Sitting about 3,000–4,000 m above sea level, the study area is located between longitude 67°52′ and 68°19′ west and latitude 22°06′ and 23°39′ south and covers an estimated area of 7,600 km^2.

Arsenic in the area is the result of volcanic activity, an abundance of ore deposits, and human activities. Endogenous and exogenous agents such as wind and groundwater circulation spread the arsenic in the atmosphere, soil, and water. Another related factor to the presence of arsenic in the area is mining, which constitutes more than 20% of the area's economic activity and was a driving force for the implementation of monitoring plans and mitigation strategies that have improved the arsenic problem in the last few decades. Arsenic is a natural constituent in lead, zinc, gold, and copper ores and can be released during the smelting process. The flue gases and particulates from smelters can contaminate nearby ecosystems downwind from the mining operation. In addition, agricultural activities in the Región de Antofagasta are chiefly associated with the Rio Loa and the Salar de Atacama hydrological basins. Therefore, a significant amount of arsenic stems from both natural and human sources (Queirolo et al. 2000).

Fig. 17.3 Study area 2. Second region of Antofagasta, northern Chile

The mean annual temperature is 11.3°C; the mean temperature is 18.7°C in the summer and 4°C in winter. Frost is present (at temperatures below 2°C) between 2.4 and 4.5 months per year. Annual precipitation during the period 1985–1995 was estimated to average 35 mm and primarily fell during summer (Gundermann 1995). Rainfall totals vary with altitude; during 1996–2005, Ojos San Pedro (at an elevation of 3,800 m) received an average of 64 mm, while Chiu Chiu (at 2,524 m) received 7 mm.

17.2.2.1 Superficial Hydrology

The major water supplies to the Salar de Atacama basin are from the San Pedro and Vilama rivers, with a total estimated input of 1,130 L/sec. The San Pedro River (formed by the junction of the Salado and Grande rivers) carries much of this input and has a flow that varies from 679 to 900 L/sec. The Vilama River is formed by the junction of the Puritana and Puripica thermal springs and has an independent network running parallel to the San Pedro River. The reported flow rate is between 213 and 230 L/sec. Both rivers have salty water. The Salar de Atacama basin is a closed basin. Water input is by snow and rain, and this water is then transported as surface water or groundwater. Water leaves the basin as a result of evaporation, evapotranspiration, or human activity. Recent research suggests that the annual average water recharge in the Salar is approximately 5 m^3/sec.

The hydrographic system of the Rio Loa comprises an area of approximately 33,570 km^2, making this river the longest in Chile (440 km). Nevertheless, the water resources come from the upper basin, which corresponds to about 20% of the area. The Rio Loa is vital to the development of the flora and fauna of the region, as it exists in an environment of extreme aridity (Fundación Chile 1993; CONAMA 2006).

17.2.2.2 Arsenic in Water Sources

The two areas with higher arsenic concentrations in the Rio Loa basin are: (a) the confluence with Rio Salado, where the occurrence of arsenic is associated with chlorine, sodium, and boron, and (b) the area of the river underneath the city of Calama, where the arsenic occurrence is associated with sulphate and copper (II) cations. The water quality is variable, ranging from very good (during snow melting) to very brackish. The dry climate in this region enhances the salt concentration in rivers. Although no specific studies on arsenic concentration have been performed, the dry climate is likely to enhance its concentration in rivers. Antofagasta is home to rivers with variable arsenic concentrations (Tables 17.3 and 17.4) related to the volcanic and geothermal origin of arsenic (Cáceres 1999; Sancha 2000; DGA-Chile 2006). It is difficult to assess the potential impact of mining activities in arsenic content in these rivers because an arsenic baseline prior to mining activities has not been determined.

Table 17.3 Range of arsenic in river water in northern Chile

River	Arsenic concentration (mg/L)
Vilama	0.6 to 0.7
San Pedro	0.4 to 0.5
Toconce	0.6 to 0.9
Lequena	0.15 to 0.35
Loa	1.5 to 2.5

Source: DGA-Chile 2006

Table 17.4 Arsenic water concentration in rural towns in northern Chile

Town	Arsenic concentration (mg/L)
Lasana	0.40
Toconce	0.40
Talabre	0.37
Caspana	Good quality
Chiu-Chiu y Ayquina	0.80
San Pedro de Atacama	0.75
Toconao	Good quality
Socaire - Cámar	0.28

Source: Cáceres 1999

The Loa River basin is the source of drinking water for the main cities of the region—Antofagasta, Calama, Mejillones, and Tocopilla—through several captures (Table 17.5) with a total volume of 1,400 L/sec. The arsenic concentration in Loa River ranges from 0.08 to 1.02 mg/L, in all cases above the established limits for human consumption.

The current environmental quality of Rio Loa is healthy but is subject to the mineralogical characteristics of the soil and subsoil through which the water percolates (CONAMA 2006). The hydrological setting of northern Chile corresponds mainly to endorheic basins and drainage systems that do not reach the Pacific Ocean. Evaporitic bodies (locally called salares, or salt flats) are commonly formed in the

Table 17.5 Superficial sources of water uptake in Loa River

Sector	Sources of uptake	Volume L/sec	As (mg/L)
Río Loa	Lequena	550	0.30
Río Loa	Quinchamale	300	0.14
Río Loa	Agua Puente Negro	29 – 86*	1.02
	Represa San Pedro-Inacaliri	50	0.50
Toconce	Toconce	490	0.77
Agua Verde	Pozos Agua Verde	32	0.08

Source: ESSAN 2001

* Seasonality

lowest part of these basins. In some cases, like at Salar de Atacama (at an elevation of 2,300 m), they are huge (3,000 km^2).

Environmental monitoring programs have been developed in the last few years by governmental and nongovernmental entities in the region, and the evolution of arsenic levels has been relatively stable in the locations that have been monitored in the last two decades. Total arsenic levels along the course of Rio Loa increase when sampling points are closer to the mouth due to the contribution of other watercourses.

Agriculture in this region is limited by soil and water contamination and water scarcity. Although agriculture production is not relevant to the economy of the country, it is an important food source for the indigenous communities that live far away from the main populated centers. Horticulture is the second-most important agricultural activity, and more than half of the agricultural lands are dedicated to annual and permanent forage crops. Cattle production consists mainly of sheep, goats, and camel-like cattle for subsistence.

Arsenic contents in alfalfa and horticulture products were analyzed by the Fundación Chile 1993. The informed values show no relation to arsenic content in soils. Alfalfa does not represent a harmful toxicity effect when it is used for green forage. Arsenic levels in beets from the region are 2.7 times higher than that of beets in the central region of the country but do not represent toxicity risks. In carrots and maize, arsenic is mainly absorbed by foliage, which is not used for human consumption, although its use as animal forage could indirectly affect people who eat animal products.

17.3 Arsenic Mitigation

Environmental monitoring is not a common practice in many countries but should be implemented to verify that current environmental quality norms are met, carry out baseline studies to obtain the necessary data for developing contamination control tools, and estimate the population's exposure to arsenic. Treatment technologies applied to reduce arsenic levels depend on a variety of factors (Table 17.6).

Industrial-scale remediation treatments for arsenic removal are the more appropriate solution if a centralized water infrastructure exists. When no distribution network is available or suitable because of population size, it is better to install low-cost technologies that are available at the household or community level. Appropriate in-home technologies should meet certain criteria to be effective. The treatment must be applicable over a wide range of arsenic concentrations, easy to use without running water or electricity, inexpensive, and readily available or reusable. It is also very important that the technology does not introduce any harmful chemicals into drinking water and that the quality of the treated water is not deteriorated with regard to other contaminants. The most effective remediation strategy for arsenic removal can be selected by taking into account the composition and physical–chemical properties of each water stream. Distances, source flow, and costs are among other important aspects to be considered.

Table 17.6 Design and operational parameters for different arsenic removal treatments

	Ion exchange	Activated alumina	Iron-based sorbent	Reverse osmosis	Coagulation microfiltration	Oxidation filtration	Coagulation filtration	Lime softening
Arsenic limit	160	160	16–400	160	40	40	160	80
Small systems for POU*	no	yes	yes	yes	no	no	no	No
Removal efficiency	95%	95%	Up to 98%	Up to 95%	90%	50–90%	90%	90%
Total water loss	1–2%	1–2%	1–2%	15–75%	5%	1–2%	1–2%	2–5%
Optimal water quality conditions	pH 6.5–9 <5 mg/L NO_2^{-} <5 mg/L NO_3^{-} <50 mg/L SO_4^{-2} <500 mg/L TDS** <0.3 NTU*** Turbidity	pH 5.5–6 <250 mg/L Cl^{-} <2 mg/L F^{-3} <360 mg/L SO_4^{-2} <30 mg/L Silica <0.5 mg/L Fe^{+3} <0.05 mg/L Mn^{+2} $<1{,}000$ mg/L TDS <4 mg/L TOC 0.3 NTU Turbidity	pH 6–8.5 <1 mg/L PO_4 <0.3 NTU Turbidity	No particles	pH 5.5–8.5	pH 5.5–8.5 >0.3 mg/L Fe^{+3} >0.05 mg/L Mn^{+2} Fe: As Ratio > 20:1 (weight)	pH 5.5–8.5	pH 10.5–11 >5 mg/L Fe^{+3}
Operator skill required	High	Low	Low	Medium	High	Medium	High	High
Waste generated	Spent resin, spent brine, backwash water	Spent media, backwash water	Spent media, backwash water	Reject water	Backwash water, sludge	Backwash water, sludge	Backwash water, sludge	Backwash water, sludge (high volume)

*POU: point-of-use device, located where water is going to be used
**TDS: total dissolved solids
***NTU: Nephelometric Turbidity Units
Source: ARSLAND 2007; Mohan and Pittman 2007

In both study areas, arsenic levels in water are above the WHO guidelines for human consumption (10 μg/L). Solutions for reducing the concentration at the two sites include finding alternative water sources or applying low-cost remediation technologies for houses or villages. These technologies may consist of arsenic immobilization in situ (Miretzky and Fernández Cirelli, in press) or treatments with iron or iron oxides (Raven et al. 1998; Karcher et al. 1999; Sancha 2000; Sancha and Castro de Esparza 2001; Peter 2005), or they may involve the use of adsorbents (Pollard et al. 1992; Daus et al. 2004; Ng et al. 2004; Mohan and Pittman 2007). Using iron compounds to remove arsenic has proven successful in Chile (Karcher et al. 1999; Sancha 2000). In addition, household-level point-of-use (POU) arsenic removal systems can make an important contribution to safe drinking water, especially in isolated areas and for rural populations in developing countries.

In the region of Antofagasta, the greatest exposure was recorded during 1958 and 1970, when the levels of arsenic in the water fluctuated between 0.8 and 0.9 mg/L. By the mid-1970s, abatement efforts began with arsenic treatment plants. Between 1979 and 2002, the level of arsenic decreased to 0.05 mg/L—the maximum amount accepted in Chile—but still five times higher than that recommended by WHO and the US Environmental Protection Agency (Hopenhayn-Rich et al. 2000; Ferreccio et al. 2000). Beginning in 2003, the Aguas Antofagasta Company applied a variety of different policies and reduced the arsenic levels from 0.05 to 0.01 mg/L in the region of Antofagasta, where it operates three arsenic treatment plants in urban centers. The company supplies water to the cities of Antofagasta, Calama, Tocopilla, Mejillones, and Taltal. In 2002 the Dirección de Obras Hidráulicas took control of two treatment plants located in rural communities: one in San Pedro de Atacama and the other in an area between Lasana and Chiu-Chiu. The levels of arsenic measured in the water produced by the latter ranged between 0.01 and 0.02 mg/L (Granada Meneses et al. 2003; Bustos et al. 2005).

In the study area in Argentina, the arsenic problem in rural areas continues to be of concern for the local authorities. Options for them include replacing wells that take water from shallow aquifers with those that draw from deeper ones or applying known low-cost remediation technologies. Financial aid should be given to the isolated rural population.

In Chile, alternative water sources are not available; therefore, authorities should implement remediation technologies for isolated rural populations. Urban populations are served by water treated by reverse osmosis in appropriate facilities.

Because arsenic contamination is largely a natural phenomenon, communities are likely to feel helpless. Therefore, it is necessary that the population become aware of the arsenic water contamination, its safety consequences, and possible solutions. This task is especially complicated when the high arsenic level affects isolated rural populations, which lack access to the mass media and must be notified about arsenic problems and issues individually. Most of the informative tasks should be accomplished at the school level.

Public awareness campaigns will be needed to help and support affected communities or families. Local media can also make a difference, especially when linked to group discussion among stakeholders (farmers, authorities, water users). The success of any mitigation plan depends strongly on the participation of the people. Any public awareness campaign—national, regional, or local—should reflect the different roles and responsibilities that women and men have in the provision of safe water for personal consumption and for agricultural activities. In these communities, women are in charge of water provision for domestic uses and subsistence agriculture activities. Once people are convinced that arsenic contamination is a health problem and that it is possible to obtain arsenic-free water through accessible treatments, the next step is to familiarize them with more suitable options. Only then may success be guaranteed.

Note

1. Provinces in Argentina are broken into secondary units called departamentos ("departments"), except for Buenos Aires province, which is divided into partidos.

Acknowledgments These results reflect the work carried out by the project ARSLAND (Sustainable Management of Arsenic Contaminated Water and Soil in Rural Areas in Latin America, INCO 015114, www.arsland.net). Special thanks go to Viviana Urtuvia Gatica and Cecilia Demergaso Semenzato, Centro de Biotecnología; Prof. Alberto Ruiz, Universidad Católica del Norte, Antofagasta, Chile; and partners of ARSLAND.

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Chapter 18
Evaluating the Restoration of Dryland Ecosystems in the Northern Mediterranean

Susana Bautista, Barron J. Orr, José Antonio Alloza, and Ramón V. Vallejo

Abstract Drylands in the northern Mediterranean present significant challenges for efforts to preserve ecosystem services. Warming trends combined with declining and more variable summer precipitation have come with more frequent and more intense droughts, exacerbating water shortages. Depopulation from rural uplands towards urban coastal regions, with farmland abandonment, has destabilized agroecological systems. The ensuing land degradation has influenced local hydrology, erosion rates, water quality, and water quantity. Ecological restoration combined with adaptive management can be an effective approach in response to the changing climate and environment. The development of standardized monitoring and evaluation protocols on the EC REACTION project has provided powerful insights and new tools to enhance the potential for successful restoration. The integration of biophysical and socioeconomic indicators and the collaboration between researchers, managers, and decision makers make the approach effective and sustainable. Restoration in drylands can have a marked impact on water budgets through the selection of species and the influence on landscapes and vegetation patterns. Adapting to environmental change and combating land degradation in the northern Mediterranean will require understanding the tradeoffs in ecosystem services and adjusting restoration decisions in response to monitoring and evaluating both biophysical and socioeconomic metrics.

Keywords Drylands · Evaluation · Northern Mediterranean · Restoration · Water budget

18.1 Drylands in the Northern Mediterranean: Degradation Threats and Restoration Needs

The Mediterranean Basin is characterized by the diversity of its landscape, biology, and culture and has undergone and continues to experience changing demograph-

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G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
DOI 10.1007/978-90-481-2776-4_18,

ics, livelihoods, climate, and environment. Throughout history, climate variability and intense pulses of land over-exploitation have contributed to episodes of land degradation (Pons and Quezel 1985; Margaris et al. 1996; Puigdefábregas and Mendizabal 1998), resulting in landscape changes that have crossed ecological thresholds. Once crossed, returning to functional and healthy ecosystems requires human intervention in the form of restoration (Vallejo et al. 2006a). Two critical issues concerning dryland restoration in the northern Mediterranean[1] deserve special attention: the evaluation of restoration actions and the impacts of dryland restoration on water budgets.

The Mediterranean Basin contains about 2.3 million km^2 of land and accounted for 10.3% of the world's total population (more than 630 million in habitants) in 2001 (Vallejo et al. 2006a; Population Reference Bureau 2001). The northern Mediterranean represents 1.1 million km^2 of land and 19% of the basin's population (Makhlouf 2004). The majority (~95%) of the drylands in this region are in the territory of five southern European countries: Spain, Portugal, Greece, Italy, and France (Puigdefábregas and Mendizabal 2004). During the twentieth century, population growth rates in southern Europe were high, marked by agricultural intensification in the lowlands and coastal areas, and a process of depopulation and land abandonment inland that continues today (McNeil 1992; Margaris et al. 1996; Wainwright and Thornes 2004). Population growth has slowed significantly in the last couple of decades. With some of the lowest fertility rates in recent years ever recorded, the projected population growth rate is low (ranging from –0.1% in Italy to 0.4% in France), and is projected to decline over the next 50 years (King 2000; Makhlouf 2004). Economic disparities that led to migration from rural areas in southern Europe to industrial areas in northern Europe during the postwar era have been replaced by an economic transformation fuelled by industrial modernization, tourism, and the expansion of the service sector resulting in parity or near parity in income levels with northern neighbors (Grenon and Batisse 1989; King 2000).

The Mediterranean Basin has a strong overall gradient of aridity from the northwest to the southeast. Subtropical high atmospheric pressure results in long, hot, and dry summers while the winters tend to be cool or cold and wet (Peixoto et al. 1982). Climatic conditions vary greatly over short distances, and cyclonic or convectional rainfall can be quite intense, particularly in the drier regions and during the dry season (Thornes 1996). Drought of variable duration is common (Vallejo et al. 1999). The warming trend in the Mediterranean over the past 30 years likely exceeds the warming rate of any other comparable period over the past 500 years (Luterbacher et al. 2004). A mean temperature increase of 3.4°C is projected over the next century in the northern Mediterranean, with the greatest warming and highest variability in the summer (IPCC 2007a; WBGU 2008). Long-duration summertime droughts will be more frequent (Lehner et al. 2006; Blenkinsop and Fowler 2007), commence earlier in the year, and last longer (Beniston et al. 2007).

Climate cycles, variability, and change have a significant impact on the hydrologic cycle in the Mediterranean region. Mariotti et al. (2002) estimate that during the last half of the twentieth century, the Mediterranean atmospheric water deficit increased by 9% annually, including a 24% increase in winter. They suggest this has led to a 500 mm/yr freshwater deficit. The positive trend of the North Atlantic Oscillation (NAO) index during the last quarter of the twentieth century also has been correlated with a significant decrease in available river flow and water resources, particularly in the southern Iberian Peninsula (Trigo et al. 2004). The higher temperatures increase soil-water evaporation rates, impacting agriculture and ecosystems (IPCC 2007b). When these climate trends were considered in predictive models and scenarios of land use change for Europe, the Mediterranean region was by a large degree the most vulnerable to species loss, distribution shifts, catastrophic events such as severe wildfire and water shortages, and the loss of agricultural potential (Schröter et al. 2005).

Agriculture amounts to 60% of the total water demand of northern Mediterranean countries, and crop production is sensitive to climatic variability and structural deficits (Iglesias et al. 2003). Water shortages have been exacerbated by rising demand for irrigation water, domestic consumptive use increases associated with the rise in tourism, population migration to the coasts, and poor management of the existing resources (Wainwright and Thornes 2004). While irrigated agriculture continues to expand in southern Europe, groundwater extraction patterns may not be suited to adapt to these changes, particularly in locations where withdrawals are projected to exceed availability, resulting in severe water stress and aquifer degradation (Henrichs and Alcamo 2001). Groundwater demand, climate-enhanced water shortages, and more extreme weather events are impacting cultural practices (crop selection, yields, and agricultural extensification) in the northern Mediterranean (Olesen and Bindi 2002).

Climate change and changing land use patterns and practices are impacting water budgets and triggering land degradation. Agricultural intensification in the lowlands has led to contamination of soils and water with nitrates, pesticides, and even heavy metals (Stoate et al. 2001). Agricultural land abandonment in the marginal uplands has severely impacted landscape structure (e.g., collapsing terraces), and has led to deteriorating soils, increased erosion, and an ecological transformation tending towards bushland, scrubland, and forestland expansion (Vallejo et al. 1999; Wainwright and Thornes 2004; Chauchard et al. 2007). In addition, large afforestation projects were initiated in the first half of the twentieth century, resulting in the plantation of millions of hectares of mostly pine in northern Mediterranean uplands (Vallejo 2009). The vegetation transitions (both successional and through afforestation) have stabilized soils and other landscape features (i.e., abandoned terraces), but they also have significantly increased flammable fuel loads. Combined with drier climate conditions, the unintended consequence in some locations has been an increase in larger, more severe wildfires in the northern Mediterranean (Vélez 1997; Moreno et al. 1998), ironically leading to increased soil erodibility and accelerated erosion rates (Giovannini et al. 2001).

Drylands present significant challenges in efforts to reverse land degradation trends. Water is the primary limiting factor for both natural and human dryland systems (Noy-Meir 1973). Dryland ecosystems tend to have low resilience and slow recovery after disturbances. The resulting loss of ecosystem functioning and structure can lead to abrupt, discontinuous transitions (Kefi et al. 2007), leaving no realistic chance of self-recovery at management time scales and thereby requiring external inputs from restoration actions.

18.2 Mediterranean Dryland Restoration

Significant national-scale attempts to restore degraded drylands in the northern Mediterranean date back to the late nineteenth century and became widespread during the twentieth century. These efforts were mostly based on large afforestation and reforestation programs with tree species, mostly pines (see Chapter 1). These massive plantations were carried out in all Mediterranean countries. For example, 3.8 million hectares (ha) were reforested in Spain during 1945–1986 (Ortuño 1990).

Soil and water conservation was the primary goal for most of the past restoration projects in the northern Mediterranean. Performed in the framework of watershed protection programs (RTM, Restoration of Mountain Terrain in France; Hydrological and Forest Restoration Programme in Spain; etc.), a number of projects were designed after major floods in the respective watersheds (Ortuño 1990; Vallauri et al. 2002). The stabilization of sand dunes was also an important goal of many restoration programs such as the Sardinian effort to control moving dunes in the 1930s (Vallejo et al. 2006b). Wood production was a complementary objective in many cases; economically valuable conifers were commonly used to add value to restoration in the target areas. Some projects were specifically aimed at recovering species or communities of particular interest (e.g., cork oak forests in southern Portugal and Spain). Most restoration programs had an additional objective of improving rural economies through the creation of jobs and livelihood opportunities through the project and the anticipated income generated by the expected increase in the provision of forest products.

The main species planted were conifers, mostly pioneer pine species, such as *Pinus brutia*, *P. halepensis*, *P. nigra*, etc. Exotic species also were planted. In many cases, the strategy was first to introduce a fast-growing pioneer species (usually a pine) to create a temporary sheltering system (with additional timber production advantages), with the assumption that this species would facilitate the introduction of native hardwoods, mostly oaks (Barbéro et al. 1998). For most projects, post-planting care, especially thinning, management planning, and/or monitoring programs were lacking. However, reinforcement planting and seeding were very common.

The results obtained from large-scale afforestation programs have varied greatly depending on the quality of the methods applied, their adaptation to local conditions, and the quality of the plantation management; some programs have resulted in magnificent forests (Vallejo 2009), but others failed in accomplishing their goals. In addition, the extensive pine plantations resulted in large and homogeneous areas covered with flammable, even-aged pines, which have facilitated the spread of the large fires that have been occurring in southern Europe over the last few decades.

During the last quarter of the twentieth century, socioeconomic changes in southern Europe changed the social demands placed on wildlands and, accordingly, new restoration goals emerged. Projects designed to prevent wildfires, improve silvopastoralism, increase the recreational and cultural use of wildlands, increase biodiversity, and recover native woodland ecosystems were conducted in the framework of these new demands (Vallejo 2009). Recent afforestation measures for setting aside agricultural lands, promoted under the Common Agricultural Policy of the European Union, were conceived according to these new demands. Thus, the broadleaved species represented approximately 60% of the planted area, with cork oak and evergreen oak stands occupying a dominating position—essentially the reverse of the planting trends in previous decades (Picard 2001). Since the 1990s, mitigating climate change has become a core objective of afforestation and reforestation programs worldwide.

Parallel to the changes in the conceptual frameworks and approaches for dryland restoration, the last few decades have witnessed remarkable advances in restoration techniques. Technological innovation is needed to overcome the very limiting conditions of many degraded drylands. Recent innovations in nursery and field techniques aimed at increasing water availability and plant water-use efficiency have greatly increased restoration success in Mediterranean drylands (see recent reviews in Cortina et al. 2004 and Vallejo et al. 2006a). Other techniques based on the use of nurse plants and site heterogeneity recently have shown promising results, as has the recovery of traditional water harvesting and low-cost irrigation techniques (Bainbridge 2007).

18.3 Evaluation of Forest Restoration Projects in the Northern Mediterranean

Despite a long history of restoration actions and the derived restoration expertise accumulated across southern Europe, goals set are not always achieved in Mediterranean dryland restoration. The considerable challenge degraded drylands present, the common tendency to repeat treatments without questioning their efficacy or applicability to different bioclimatic zones, and the lack of long-term management programs for the restored areas all contribute to these failures. The lack of and/or insufficient access to available information on restoration actions combined with poor communication and knowledge exchange are limiting the application of the best technologies and approaches.

There is a consensus on the need for the evaluation and dissemination of the results of restoration and management actions. The information needed goes beyond the determination of failures and successes in terms of quality control and/or technical testing. The assessment of restoration actions must also entail interactive training and educational tools that integrate the restoration effort into the learning process so that future efforts benefit from past experience. Formative evaluation is a critical component of an adaptive management approach to restoration. Regular feedback from the evaluation process provides the necessary input for the fine tuning of treatments applied, and helps managers adapt restoration strategies and techniques in response to environmental changes and better accommodate social demands (Murray and Marmorek 2003; Vallauri et al. 2005; Aronson and Vallejo 2006). Success will depend on incorporating what we learn from past efforts so that we can improve our understanding of the impacts of restoration actions and strategies on socioecological systems. Evaluation helps with midcourse adjustments on a given project and with facing the uncertainty inherent to ecosystem dynamics. It also helps us answer the critical larger questions faced in all dryland restoration: What is the potential impact of restoration on biodiversity? How can restoration affect landscape patterns and functions? What is the potential of restoration for enhancing carbon sequestration? And, of particular importance in drylands, what are the impacts of restoration actions on water budgets?

Despite its well-acknowledged benefits, an evaluation component is rarely included in restoration programs; completed projects often are not adequately monitored and assessed (Clewall and Rieger 1997). As a result, restoration expertise remains underutilized, knowledge on the feasibility and cost-effectiveness of restoration strategies for a variety of environmental and socioeconomic conditions is lacking, and lessons are often learned too late. In recent years, however, monitoring and evaluating restoration projects have received greater emphasis (Vallauri et al. 2005) and, accordingly, there is a new demand for suitable indicators and methods to evaluate the restoration efforts across a variety of ecosystems and landscapes. Because land condition results from coupled human–environmental processes, it is crucial to develop integrated evaluation methods that consider ecological, technical, and socioeconomic issues and their interactions (Clewell and Aronson 2006; Zucca et al. 2009). Biophysical and socioeconomic indicators that relate to ecosystem integrity and services and to human well-being are essential for the meaningful evaluation of restoration projects (Vallauri et al. 2005).

A number of recent initiatives have addressed the need to establish monitoring and evaluation protocols for rehabilitation and restoration projects (e.g., Davis and Muhlberg 2002; Thayer et al. 2003; Gerstein and Harris 2005; Collins 2007). However, most of the available guidelines and protocols are based solely on biophysical indicators. The limited emphasis on socioeconomic, policy, and cultural measures hinders both the explanatory value of an evaluation and our capacity to incorporate what has been learned into future decision making. For northern Mediterranean drylands, an integrated approach to evaluate forest restoration actions was recently developed by the REACTION project (Bautista et al. 2004), which is funded by the European Union (EU) and involves research groups and natural resource managers from all European Commission (EC) Mediterranean countries.

18.3.1 The REACTION Approach: An Integrated Forest Restoration Evaluation Framework

The primary objective of REACTION (Restoration Actions to Combat Desertification in the Northern Mediterranean) was to develop tools for evaluating forest restoration projects in the Mediterranean region. The REACTION evaluation protocol was not only conceived as an evaluation methodology, but also as an information system designed to compile and disseminate the information derived from

Table 18.1 General structure of the REACTION evaluation protocol

Sections	Topics
I. General Information	General Description
	Data Sources
II. Site Description	Climate
	Topography
	Geology
	Soils
	Ecology
	Degradation Impacts And Drivers
III. Restoration Process	Goals
	Planning
	Cost & Financing
	General Technical Description
	Monitoring and Assessment Programs
	Environmental or Technical Units
IV. Technical Description by Restoration Units	Unit Description
	Specific Environmental Characteristics
	Promotion of Autogenic Restoration
	Prior Action on Vegetation
	Site Preparation
	Planting & Seeding
	Field Treatments/Maintenance/ Management
V. Assessment by Restoration Units	Plantation/Seeding Results
	Structure & Biodiversity
	Functions & Processes
	Stand/Unit Health
VI. Project Assessment	Landscape & Environmental Assessment
	Socioeconomic Assessment
VII. Evaluation Summary	
VIII. Expert Judgment	

an integrated assessment of the restoration projects evaluated. The protocol is based on a wide variety of indicators focused on both human and natural systems, addressing stand, ecosystem, and landscape scales. To analyze constraints and opportunities for restoration and to allow for comparisons between different technical approaches, site environmental conditions and a technical description of the restoration project are core to the evaluation protocol (Table 18.1).

The REACTION approach is based on three main criteria: (1) degree of achievement of specific initial project objectives, (2) comparative analysis between pre-restoration degraded conditions and current conditions, and (3) analysis of current quality of the restored system irrespective of initial project goals (Bautista et al. 2004). The evaluation methodology considers three major categories of objectives: structural goals, functional goals, and socioeconomic and cultural goals. Selected indicators include standardized ecological, environmental, socioeconomic, and cultural attributes that are relevant for Mediterranean conditions. The biophysical evaluation focuses on both the structural and functional quality of the restored ecosystems and landscapes and prioritizes indicators related to hydrological processes, as they are particularly relevant in desertification-prone drylands (e.g., flood frequency, drainage quality, erosion type, erosion severity, degree of soil crusting, etc.). The socioeconomic assessment focuses on information about land use; ecosystem goods and services; employment; and the recreational, educational, and cultural values of the restored land (e.g., livestock species and population, types and amount of timber and non-timber products, provision of jobs, number of visitors, cultural sites, etc.). Parallel to assessing these indicators is a process where expert judgments of both natural resource managers and researchers involved in the evaluation of the restoration project are obtained. This allows for engagement between researchers and managers and provides the opportunity to gain insights not readily available in the assessment of raw data.

The REACTION evaluation methodology has been applied to 40 forest restoration projects implemented in Greece, Italy, France, Spain, and Portugal, ranging in size from ~100 to 3,500 ha.[2]

The projects are representative examples of the varied approaches to dryland restoration in the northern Mediterranean. The main goal of most of the evaluated projects (78% of the cases) was erosion and flood control; job creation as part of larger efforts to sustain rural populations and livelihoods was an important complementary goal in many cases. Reforestation was aimed mostly to restore pine forests and mixed pine–oak forests (65% of the evaluated projects). The projects succeeded in terms of achievement of original functional and/or structural goals (Fig. 18.1); however, evaluation results also showed that the current quality of the restored ecosystems varies significantly between sites.

At present, soil surface conditions (assessed through indicators such as the amount of bare soil, degree of soil crusting, and type and severity of erosion features, among others) are slightly or seriously degraded in 50% of the cases. Some restored sites (e.g., Sierra Espuña in southeastern Spain) resulted in mature, multilayered mixed forests, with a biodiverse and potentially resilient understory. In other cases, the restoration effort led to monolayered, even-aged pine forests, with poor tree regeneration and health, and the sites still exhibit some degree of soil erosion, low capacity for water conservation, and low values of species richness. Even though, to some extent, all the evaluated projects enhanced ecosystem services as compared to previous conditions, very few of them had a sustained impact on the well-being and stability of rural populations. However, in most cases, the restoration actions produced certain indirect socioeconomic benefits, such as the enhancement of tourism in the project sites.

18.4 Dryland Restoration and Water Budgets

One of the primary concerns in the northern Mediterranean is the availability of water. Assessments of past restoration efforts highlight the clear interactions between these efforts and water budgets. What conclusions can be drawn from the evaluation and overall analysis of past and recent restoration actions?

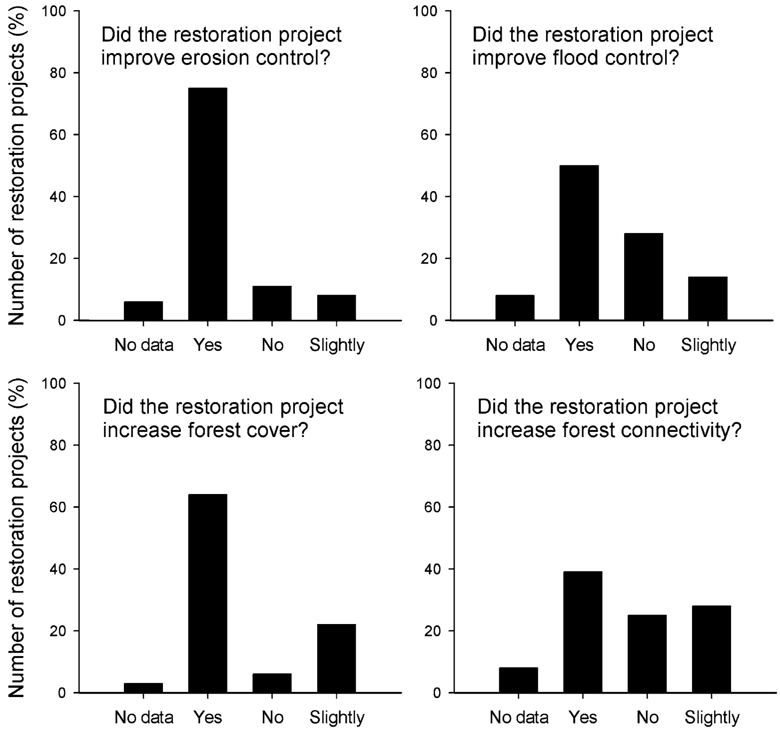

Fig. 18.1 Degree of achievement of functional (erosion and flood control) and structural (forest cover and connectivity) goals of large-scale restoration projects conducted between 1870 and 1990 in the northern Mediterranean and evaluated through the REACTION integrated-assessment protocol. (Source: REACTION database (http://www.ceam.es/reaction/database)

It is clear that the restoration of forests and woodlands has played an important role in soil conservation and flood control in Mediterranean drylands (see Fig. 18.1). In saline-prone areas, forest restoration may also help prevent the rise of saline groundwater to or near the soil surface (Walsh et al. 2003). Furthermore, the restored vegetation can filter and trap sediments and other water pollutants, thereby greatly improving water quality, a vital contribution to the hydrology of the targeted watersheds. Forest restoration also has been proposed as a way to increase rainfall, though it has been argued that only large-scale efforts would produce a tangible positive feedback effect on rainfall (Avissar and Otte 2007). In addition, reforesting denuded lands in high-elevation areas could result in a substantial increase in water inputs through the capture by the tree foliage of horizontal precipitation from fog or clouds (Schemenauer et al. 1995). Despite the important role of forest and woodland restoration in soil and water conservation, as demonstrated by the evaluation of forest restoration projects in the northern Mediterranean, there is a growing consensus that the potential of upstream restoration efforts to protect against downstream floods has been overestimated (Calder et al. 2007). This tendency to overestimate is particularly apparent in large-scale watersheds or river basins and is now a matter of ongoing debate (FAO-CIFOR 2005).

Forest restoration in drylands often has been based on the assumption that forests maximize water yield by increasing aquifer recharge and base stream flow. Recent forest hydrology research suggests a different scenario, particularly in arid or semiarid ecosystems where tree canopies can actually reduce water yield through interception of precipitation and evaporation and transpiration from the foliage (Calder 2007; Van Dijk and Keenan 2007). In general, forests use more water than shorter types of vegetation because of higher evaporation. Consequently, in semiarid areas where trees may consume all the rainwater (Schiller and Cohen 1998), afforestation must be carefully considered, as more water could be harvested from bare or poorly vegetated lands to mitigate drought or to irrigate high-value agricultural crops (Malagnoux et al. 2007). However, such an option should be weighed against the value of many other services and goods supplied by forests and woodlands such as erosion control, improved water quality, carbon sequestration, biodiversity, recreation, and the provision of fuelwood and other forest products.

The effect of dryland restoration on water budgets depends on the type of plant community and the associated complexity of the canopy layers. Thus, for example, in a mosaic landscape of dry grasslands and Aleppo pine (*Pinus halepensis*) plantations in semiarid southeastern Spain, pine forest patches have been shown to reduce runoff as compared with dry grassland patches, but only when a shrub understory was present beneath the pines. Forest patches with pines and shrub understory showed higher evapotranspiration rates than pine patches with grass understory; dry grassland patches showed the lowest evapotranspiration rates and the highest deep drainage values (Bellot et al. 1999; Chirino et al. 2006). These results are in agreement with the evaluation results of forest restoration projects using the REACTION methodology, which pointed to multilayered forests as the most effective forest structure in terms of soil conservation potential (Vallejo et al. 2006b).

Recent empirical research has shown that not only vegetation cover and type but also the spatial pattern of plant patches have a significant impact on controlling runoff and sediment yield in drylands, with the spatial connectivity of runoff-source areas playing a major role in this control (Bautista et al. 2007; Mayor et al. 2008). Similarly, at the landscape scale, the hydrological response to restoration not only depends on the amount of land restored and the type of plant cover, but also on the spatial pattern of the restored patches within the watershed, as even small restored patches could have a major impact on the hydrological and sediment connectivity in the landscape (Vanacker et al. 2005).

Climate change is altering the interaction between forests and woodlands and water budgets (Stohlgren et al. 2007). For Mediterranean ecosystems, climate models predict a higher rate of evapotranspiration and increased summer droughts (IPCC 2007a). In this context, the role of forests in regulating water quality and quantity is uncertain. Where forest planting is contemplated for climate change mitigation, it is essential to ensure that the restoration effort will not accentuate water shortages. It is clear that restoration goal setting, species selection, and technical approaches must adapt to the new conditions resulting from climate variation.

18.5 Lessons Learned: Implications for Practice

The evaluation of the varied successes and failures of past restoration actions in Mediterranean drylands, together with the advances in dryland ecohydrology and ecological restoration research, form a valuable foundation to address the challenges faced by those working to restore drylands in the twenty-first century. The main lessons learned point to the following core aspects, which should always be considered when planning and implementing restoration actions:

- *Interactions and trade-offs between services supplied by the restored areas*. The prioritization of the provision of specific services through restoration actions must be based on the understanding of their interactions and trade-offs, as all ecosystem services do not necessarily covary. Dryland restoration should embrace multipurpose approaches aimed at achieving both ecological and social progress. The impacts of restoration on multiple ecosystem processes and attributes, such as carbon and water cycles, and biodiversity must be taken into full consideration.
- *Water balance dynamics*. The interactions and trade-offs noted above are particularly apparent when viewed from the perspective of water. A key challenge for forest restoration in drylands is to maximize the multisectoral benefits provided by forested areas without detriment to water resources. The analysis of the climatic and socioeconomic conditions today and under future scenarios and the associated implications for local water availability and water demand must always be considered. Woodland restoration can have a marked impact on water budgets through the selection of species and the spatial structure and size of forested patches and gaps. Appropriate silvicultural measures can be applied to maintain the yearly water consumption below the yearly water inflow including, when necessary, conversion to more sustainable vegetative cover in line with climate and land use trends and associated water dynamics.
- *Landscape perspective*. Every restoration program should be considered at the landscape level. The functioning of landscapes is strongly linked to their structure. Within a landscape, patches are not isolated, and the interactions between units and transfers of materials across system boundaries have to be taken into account. Dryland restoration actions should be designed according to natural landscape structure and vegetation patterns with the aim of recovering desirable landscape processes to induce positive changes. Furthermore, large restoration programs based on extensive implementation of schematic approaches are not able to adapt to specific local socioecological constraints and/or opportunities, and may even have negative impacts.
- *Long-term perspective*. Very often the duration of restoration programs is too short, the long-term dynamics of the newly established systems are not fully considered, and/or restoration plans underestimate the time required for ecosystem recovery. A long-term perspective should inform the design of restoration objectives and assessment protocols. Project duration should allow for effective adaptive management and for monitoring and assessment of project impacts and sustainability.

- *Prioritization of targeted areas and restoration efforts*. To manage land and resources wisely, restoration actions should be implemented only where and when they are required and when they are sustainable. Trajectories of ecosystem degradation and recovery commonly exhibit complex dynamics, thresholds, and rapid shifts that can hamper the identification of the most suitable areas and the amount of ecotechnological effort needed for maximizing the benefits from restoration. A direct relationship between ecosystem functional status and the efforts needed to restore it cannot always be assumed.
- *Coupled human–environmental frameworks*. Land degradation is framed within multiscale, coupled human–environmental dynamics, and therefore the approaches for restoration implementation, assessment, and evaluation also must be. However, the importance of restoration for local economies and for the people most directly impacted are still largely neglected in natural resource management policy and decision-making processes. The development of participatory approaches in the design and assessment of restoration actions, including capacity building and knowledge transfer, is critical to improving the adoption of cost-effective, environmentally sound restoration measures. Local ecological knowledge needs to be integrated with scientific information and technological innovation to design strategies specifically tailored for drylands restoration.
- *Monitoring, evaluation, and knowledge transfer*. The dynamic nature of degradation and recovery processes and their drivers, and the intrinsic spatial heterogeneity of drylands, are not compatible with applying generic restoration prescriptions and then returning at a later date to see what happened. Tailoring the solution to local conditions and collecting the data on key indicators so that adjustments can be made during the restoration process is essential. Monitoring and evaluating restoration actions are central to the restoration process and can no longer be considered a minor and dispensable element in restoration programs. Accordingly, appropriate funding provisions for monitoring and evaluation must always be included in the budget of these programs. There is a need for standardized techniques and metrics for valuing and monitoring ecosystem services. The development of a complementary framework for knowledge sharing and transfer is equally crucial. Despite recent attempts to document, share, and disseminate knowledge about successes and failures of restoration actions, knowledge transfer is still a missing step in most restoration efforts. Community engagement throughout the process and bringing researchers and practitioners together are essential for long-term success. An open-access information system on restoration actions would facilitate the exchange of experiences among end users associated with the practice of restoration. Such a system could also provide tools for assisting land managers through the comparative analysis of past and current experiences through shared databases.
- *Research gaps*. Last but not least, many scientific challenges remain for biophysical and social scientists to understand not only how restoration actions affect the provision of ecosystem services in drylands, particularly those related to carbon and water cycles and biodiversity, but also how to internalize the value of those services and incorporate them into decision making. The integration of

scientific information, monitoring and assessment, evaluation, knowledge transfer, and decision support are all components of the translation of science to decision makers and the translation of societal needs to researchers.

Notes

1. Northern Mediterranean and southern Europe are used interchangeably in this chapter.
2. The acquisition of the data needed for the project evaluation was based on diverse sources: project proposals, implementation reports, management projects of the restored areas, personal interviews, publications, available maps, field assessment, etc. This evaluation and compilation process facilitated the publication and dissemination of useful information about restoration projects that in the past would have been much more difficult to access.

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Chapter 19
Old and New: Changing Paradigms in Arid Lands Water Management

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Abstract Water management paradigms and practices have evolved markedly from the post-World War II years to the twenty-first century. Changes have been particularly urgent and visible in water-limited arid lands. Notable trends include movement from an emphasis on technological, supply-side solutions toward sociological, demand-side management; from rigid top-down state control toward decentralized management; and from local or regional management arenas toward integrated, multilateral formation of water policy from a global perspective. Efforts continue to augment water supplies, but practice has shifted from tactics such as weather modification to energy-efficient desalination, wastewater reuse and, significantly, conservation, which was hardly considered in previous periods of perceived abundance. Overtaking even these efforts in importance is a growing intellectual elaboration of an integrated water management paradigm, which recognizes that each element on both the supply and demand sides of the equation contributes to the total water availability and requires consideration of linkages between urban and rural water use as well as between the domestic, industrial, and agricultural sectors. This awareness has spurred the establishment of "global water initiatives," marking a shift toward globalization of water management to achieve higher levels of integration.

Keywords Arid lands · Global water initiatives · Water history · Water management · Water scarcity

19.1 Why Arid Lands?

Why study water management issues in arid lands in particular? To paraphrase Willie Sutton, a twentieth century American bank robber, "Because that's where the water shortage is."[1] Water scarcity in arid lands brings management issues to

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G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
DOI 10.1007/978-90-481-2776-4_19,

the forefront and demands attention. The search for water management solutions is more imperative in arid lands than in more mesic areas, and so drylands provide a better laboratory for study. While the imperative to solve water management problems in drylands is often perceived as having negative drivers—such as mitigation of crippling droughts and attenuation of resource conflicts brought on by scarcity—water is also the key to unlocking the positive potential of drylands. The dryland climate in the low latitudes has much to recommend it as a place to live and grow crops: clear skies, warm temperatures, and long growing seasons. But as Koenig (1956) pointed out, "... the value of a given piece of land [in drylands] is not inherent in the land, but is the value of the available water at that point." This has always been the central challenge for development in drylands, and it is patently different, at least in degree, from the situation in more well-watered regions.

About 40% of the Earth's land area is occupied by arid lands, or those areas where rainfall is generally exceeded by evaporative demand. Although rainfall is often deficient, the uncertainty that accompanies extreme variability in rainfall amounts both in time and in space offers perhaps a larger obstacle to sustained development (Hutchinson and Herrmann 2008). Rainfall variability and general water scarcity limits the production of crops, forage, wood, and other ecosystem provisioning services. Arid lands are home to more than two billion people, or about one-third of the human population in 2000, despite the challenges that water availability presents to their productive use. Over the past century or so, climate variability has combined with increasing population to place severe strains on the limited productive capacity of arid lands, resulting in desertification. As much as 20% of the arid lands are considered already degraded. Based on rough estimates, as much as 6% of the world's population living in arid lands has been affected, while a much larger number is threatened by further desertification. The future development of arid lands may feature increased desertification and diminution of productive capacity that will threaten or even reverse improvements in human well-being. Desertification ranks among the greatest environmental challenges today and is a major impediment to meeting basic human needs in arid lands (Millennium Ecosystem Assessment 2005).

In the world's arid lands—many of which are experiencing rapid population growth—palpably growing shortages of water and productive soil preclude the agricultural production increases that would be necessary to support the societies in these areas. The inexorable result of these processes has led to a dwindling food supply per person.[2] Throughout the past decades, observers such as Bertram T. Dickson (1956), who attended a seminal arid lands conference in 1955, have wondered whether adequate food requirements of the people can be provided from present sources. Crisis has been postponed by increases in agricultural productivity brought about by expanded use of inorganic fertilizers, chemical herbicides and insecticides, improved seed, and, perhaps most importantly, irrigation in arid lands. Genetically modified crops are the latest addition to the list. But limits again are looming: Paul Krugman (2008), who was awarded the 2008 Nobel Prize in Economics, sees that "... we're running out of oil, running out of land to expand food production and generally running out of planet to exploit." It is in the theater of arid lands that the three-act drama of permanent scarcity, hard limits, and forced sustainability will first play out.

19.2 Water Management Issues in Arid and Semiarid Lands

Developed and developing countries typically feature three overarching water-management concerns. The first is how to locate, extract, and make use of ever-more water to satisfy growing demand. The other two concerns are interconnected: how to avoid abuse and over-exploitation of water supplies, and how to govern the allocation of scarce supplies among numerous strident claimants. In many countries, surface waters are well explored and their limitations are known; locating new, exploitable sources of groundwater is becoming less and less likely; and wastewater reuse is coming to be seen as the last source of "new" supply. In developed countries, extraction and delivery infrastructure is usually in place, mature, and well maintained, so the spotlight is on how to manage pollution, excessive diversion of surface waters, and over-pumping of groundwater, and on the legal and socioeconomic aspects of allocating a finite water supply. However, this is not yet the case everywhere, and historically all countries in drylands have placed heavy emphasis on developing water supplies. Further discussion of managing the demand side and supply side, discussed below, is useful for informing current strategies for water management in both developed and developing countries and in transboundary regions.

Within the three umbrella groupings of water management issues, numerous specific concerns can be listed. Some distinction can be made between the suite of issues uppermost on the agenda of developing countries versus those of developed countries, but there is also some overlap.

19.2.1 Issues in Developing Countries

In developing countries, mostly in contrast to prevailing conditions in developed nations, salient issues include the following: an insufficient tax base to raise revenue for investment in establishing and improving water infrastructure; inadequate mapping of aquifers; pollution from pesticides and fertilizers of streams, rivers, and aquifers; an insufficient safe water supply infrastructure; inadequate sanitation and treatment facilities; a shortage of trained management and technical personnel; management regimes that lack transparency, public participation, and integrated planning; precedence of economic development over environmental protection; environmental and public health consequences of large dams; shortages of energy leading to irregular operation of pumping and treatment; a lack of capacity to monitor and regulate water use; and local conflicts over water rights, often between pastoral groups and agriculturists.

These characteristics often are indicative of largely agrarian economies striving to exploit available water for both rural and urban use, and, optimistically, still exploring for new sources of supply. Environments such as these may offer good potential for improving treatment and supply, reducing waste, abating gross pollution, and otherwise maximizing benefits from water use. In such places, however, fundamental obstacles of cost and capacity are more difficult to overcome than in developed countries. In some political systems, government control of water management may be fairly unified in principle but difficult to implement in practice. Local conflicts over water may be ameliorated by increased supply (in conjunction with other remedies), but such remedies are likely to prove only temporary. In the long term, equity and sustainability of water management will need robust political solutions.

While developing countries generally are occupied with internal or limited regional water management, they sometimes attempt to address larger-scope, international water issues. In Africa, for example, the countries of the Nile basin are recognizing the potential for conflict between upstream and downstream users, the limitations of any technical solution, and thus the need for serious diplomacy to manage the river system. Likewise, the four countries of the Senegal River basin, Guinea-Conakry, Mali, Mauritania, and Senegal, created an Organization for the Development of the Senegal River (OMVS by its French acronym) that aspires to whole-basin technical management and political governance of water and proximate land resources. This ambitious project is attempting to address in an integrated way and on a large spatial scale the interests of upstream and downstream users with regard to water supply, flood control, irrigation, navigation, public health, power generation, and a host of other issues that derive from impoundment and infrastructure projects. Alongside technological approaches, socioeconomic and equity considerations have an important role in OMVS, notably in conditioning such effects as a modified flood regime for traditional recession agriculture and saltwater intrusion into delta aquifers. The need for trade-offs is explicitly recognized, and optimal—rather than maximal—solutions are sought.

19.2.2 Issues in Developed Countries

Over time, the integrated, complex water management paradigm has come to be recognized as necessary in developed countries in arid regions facing the real limits of water supply. Conservation, optimal allocation, and wastewater reuse are necessarily emphasized more than such strategies as development of new sources and large-scale interbasin transfers. Specific water management concerns characteristic of developed countries are numerous: industrial and agricultural pollution of rivers, lakes, and aquifers; siltation of reservoirs and salinization of irrigated soils caused by dams and river management techniques; over-exploitation of aquifers; over-allocation of surface waters; insufficient protection of the quality of aquifers and surface waters; pressure on supplies in rapidly growing urban areas; undervaluation of water and inequitable pricing schemes; lack of uniform management and regulation regimes (especially in the United States); interjurisdictional disputes and conflicting agency priorities; inadequate valuation of instream flows for protection of riparian zones and use of waters for recreation; and a general paucity of integrated planning that includes land use.[3]

Water supply stress in developed countries stems partly from simple population growth, but more importantly it is caused by intensification of per capita water use. Higher incomes create economic demand for greater consumption of meat, which embodies more "virtual water" than cereal crops consumed directly (Allan 1997; Smil 2008) (see Chapter 7). Numerous other aspects of rich-world life also show the intensification of water use, from golf courses and landscaping in the desert to the glass of ice water in a restaurant that requires eight additional glassfuls of water to produce. While industry is generally a far less intensive water user than agriculture, some modern industries such as semiconductor fabrication are inordinate water consumers. With supply constant or even shrinking due to climate trends, the developed countries are left still looking for appropriate water management solutions.

19.2.3 Some Common Issues

In both developed and developing countries, shared concerns include loss of arable land, lack of surface water, and pressure on urban settlements; problems caused by persistent drought, climate variability, and climate change; soil salinization and loss of fertility from over-pumping groundwater; transboundary conflicts, especially between upstream and downstream users; dominance of engineering fixes over other possible approaches; resistance to change by entrenched interests; insufficient human resources and capital; old, poorly-maintained, or inadequate infrastructure; weak civil society; and reliance on closed, top-down, technocratic modes of water management.

The above concerns are fundamental and represent a broad area of overlap in the water resource management plight of rich and poor nations; they have become essentially global concerns. Two perceptual shifts have accelerated in recent decades: from nationalist thinking to globalized thinking about the "Earth system," and from an economics-based religion of rapid and everlasting growth to the idea that there are physical limits to growth on Earth, and we may be seeing them sooner rather than later, especially in arid lands. There is also a growing awareness of the inequities that might be created between present and future generations as we preempt their use of our shared planetary resources by depleting or exhausting them. These shifts have put considerations of socioecological sustainability in bold relief and given them some urgency, if not much clarity. One approach to examining the sustainability of water management is to look back at historical strategies and see which ones have proved unsustainable and which ones have persisted into the present and may continue into the future.

The history of large-scale water management is long, dating back thousands of years. Some historians have sought to explain the politics of past water management practices.[4] Other scholars, recognizing the importance of engineering and public works, have studied the evolution of water-related technology. Still others have written about the significance of cultural values for such societies as ancient Egypt, Mesopotamia, China, India, medieval and pre-modern Europe, the Islamic Middle East, and colonial Latin America. Finally, economic historians have viewed water as a valuable commodity that is central to national wealth. Each of these and other comparable retrospective points of view have some resonance with contemporary issues, but offer limited predictive capacity. The profound changes in the world over the past century (population explosion, mechanized agriculture, industrialization, computers, and now globalization, to name a few) have made it difficult to tease out accurate insights for today. To gain a more contemporary understanding of water management and sustainability, we will look at more recent history: the post-World War II years.

19.3 Context of Water Management in the Postwar Decades (1945 to mid-1970s)

After the trauma of World War II, the general feeling in much of the world turned to one of optimism. A key component of this was trust in technology to rebuild infrastructure and create wealth, aided by avenues of multilateral diplomacy, which were offered by the newly created United Nations (UN) to preserve peace and stability. The war had accelerated the development of a range of technologies (nuclear weapons, radar, Spam®) that jump-started intensive postwar reindustrialization. With the conversion of boosted manufacturing capacity from war materiel back to civilian commercial products, the pace of production and trade increased, rapidly boosting living standards. These years saw dramatic advances in "big science" such as civilian application of nuclear energy; land-alteration technology such as river diversions; and green-revolution agriculture, which permitted Mexico and other developing countries to achieve self-sufficiency in wheat in the 1950s and 1960s. Throughout much of the world, economies were growing quickly with inputs of cheap energy, cheap building materials, and cheap water.

There was some recognition at the time, greatly clarified by hindsight, of the systemic limitations of the immediate postwar period. The space age had not yet arrived but was close. The Soviet Union's Sputnik launched in 1957, and the world's first weather satellite, TIROS-1, was launched by the United States in 1960. It would still be another decade before the world would see itself from space as a fragile, delimited sphere in the Apollo 8 mission's photograph of "Earthrise" over the lunar horizon, and before synoptic views of the Earth and its resources from satellites would become routine. The immediate postwar decades also were not yet a true "information age," as digital computing was still in its infancy. Scientists were hampered by the ironic twin problems of a lack of data and a lack of computing power to process what data were available. Data storage and transmission were rudimentary by today's standards.

A third feature of the postwar period is that it was not completely peaceful, with the overhanging cloud of the Cold War. The arms race diverted material and human resources from civilian commerce, and military adventurism in Southeast Asia and elsewhere was costly and problematic. More relevant to water management, Africa, including the Sahel, became a battleground for influence between the Eastern bloc and the West through large-scale aid programs (McNeill 2000). Dams were built, impounding huge reservoirs, with as much thought given to global geopolitics as to local environmental effects. Other programs, such as the US Peace Corps, exposed a new cadre of rich-world workers to alternative ways of managing water and other resources in settings different from what they were used to. The aid ethos at that time was to doggedly transfer technology and techniques from the first world to the third world at the expense of traditional technology, and thereby to induce agricultural development and industrialization according to the western or Soviet models. Results were mixed but generally disappointing, and ample opportunity remains for improvement on that approach. But ulterior motives notwithstanding, both the capitalist and socialist visions of postwar transformation ostensibly were undertaken to benefit humankind by promoting economic development and social well-being.

After World War II, a new awareness of water as a valuable resource arose in the global arena. In large measure, the changed perception of water can be attributed to a number of momentous postwar developments. First, in the wake of the six-year upheaval, a strong sentiment arose for multinational approaches to avoiding new wars. In spite of the failure of the League of Nations—an earlier attempt at global governance and peacekeeping—the UN was created in 1945. The signatories of the UN Charter recognized that many of the world's problems transcend political borders, and like issues of war and peace, are best addressed multilaterally (Victor and Skolnikoff 1999; Keohane et al. 1994; Udall and Varady 1993). Additionally, reflecting their idealism, the UN's founders recognized that reducing or preventing military action was not a sufficient means to achieve peace. It would be just as important, they believed, to address the roots of conflict by improving human conditions.

The convergence of these two sets of principles—concerted multilateralism and an integrated view of the causes of conflict—led directly to the establishment within the UN of a family of agencies to tackle global issues relating to health, nutrition, education and science, economic development, and human rights and welfare. During the 1950s and 1960s, these agencies spearheaded the earliest global resources initiatives, such as the International Geophysical Year (IGY) of 1957–1958 (Chapman 1959), the Arid Zone Programme that began in 1950 (Batisse 1988, 1993), the International Hydrological Decade of 1965–1974 (Hudson et al. 1996; Szöllösi-Nagy 1993; Clifford 2002), and the Man and the Biosphere Programme (MAB), which was conceived in 1968 and has operated since 1971 (Batisse 1988; Otte 1997). The advent of these new institutions had strong implications for the management of shared resources such as water.

19.4 Comparison of Postwar and Current Ideas in Water Management

Against the immediate postwar background, a set of two International Arid Lands Meetings were convened in New Mexico (USA) in 1955 and organized by the UN Educational, Scientific and Cultural Organization (UNESCO) and the American

Association for the Advancement of Science (AAAS). These meetings were "centered upon those areas of investigation where prediction of the future currently must be based upon insufficient understanding and data" (White 1956). They yielded a volume in 1956 entitled *The Future of Arid Lands*, edited by Gilbert White. In recognition of the 50th anniversary of that book, Hutchinson and Herrmann (2008) issued a reconsideration, *The Future of Arid Lands—Revisited, A Review of 50 Years of Drylands Research*. Much of the following discussion derives from these two sources. The primary questions asked in 1955 that addressed water management were as follows:

- What are the prospects for usable groundwater occurrence in arid areas?
- What is the practicability of locating and estimating volume and rate of natural recharge of underground water supplies?
- How practicable is it to demineralize saline water?
- How practicable is it to reuse wastewater?
- What constitutes wise allocation of available water supplies among the various needs in arid land drainage areas?

This list may appear a bit dated, but not terribly so, and somewhat surprisingly included the issue of allocation of available (limited) water resources in drylands. This management cum social science issue stands out among the other physical science questions. However, treatment of it was actually slight, and in keeping with the salient mood of the times, most of *The Future of Arid Lands* focused on (1) technical means for improving the ability to predict rainfall and hence streamflow, and (2) finding and exploiting new or additional water resources. Notably absent from the "supply-side" list is any mention of water conservation or other demand-reduction measures that could be applied to offset some of the need to increase supplies.

19.5 Groundwater

Groundwater is the subject of the first two questions listed, but the prominence and phrasing of both questions are somewhat misleading. In 1956, it was assumed that more was known about the practicalities of groundwater distribution, storage, and recharge than is implied by the questions. In fact, one of the contributors to *The Future of Arid Lands* (Bailey 1956) stated "... virtually all the readily accessible groundwater supplies have already been located and put to use ... consensus is also that we are not likely greatly to increase the water supply by new discoveries of underground sources." This pat assertion belied how little was actually known about groundwater and the magnitude of the role it would play in the total water budget. Perhaps for this reason, discussion of groundwater at the conferences was perfunctory and did not touch on major efforts to increase supplies; instead, groundwater management was viewed as part of a more general water storage strategy. Intriguingly, participants put forth the idea to reduce the amount of surface water storage behind dams in arid regions by deliberately recharging groundwater aquifers with surface water to reduce evaporation losses. But even proponents of this approach noted that the scope for its application so far had been limited (Kellogg 1956; Dixey 1956).

As distinguished from knowledge of local groundwater resource management, the conference attendees recognized that more detailed scientific analysis and broader understanding of regional groundwater hydrology were still lacking (Batisse 2005). Although groundbreaking work on hydraulic flow through porous media had been done a century earlier (Darcy 1856), the need to extend this science prompted the establishment in 1956 of the International Association of Hydrogeologists. As natural scientists and engineers, the members emphasized basic scientific understanding rather than such societal considerations as ownership rights, management and policy, and regulation of aquifer exploitation. Nevertheless, groundwater extraction was beginning to boom with the known existence of available aquifers, the development of pumps capable of lifting water from ever-greater depths, supplies of cheap fuel, and the sensible economics of irrigation. In the US Great Plains, irrigation required three times the financial investment that rain-fed farming did, but crop yields also tripled and were assured against drought. Land prices also jumped (Opie 2000). Groundwater became a significant factor in dryland development from this point onward.

A half-century later it is apparent that *The Future of Arid Lands* underestimated the general dimensions of the groundwater resource and its importance in arid lands. Since then, only one global assessment of groundwater has been conducted, in the 1980s, but it found that 96% of the world's nonfrozen freshwater supply occurred as groundwater (Mönch 2004; Shiklomanov 1993). The heaviest exploitation of groundwater took place between 1960 and 1980, at rates certainly unforeseen in 1956. Most groundwater development has been for use near the point of extraction, but spectacular departures from that have occurred. Libya's Great Man-Made River project, conceived in the 1960s, planned in the 1970s, begun in the 1980s, and still in progress, taps a huge volume of fossil groundwater under the Sahara Desert in the south of the country and pumps it 600 km to the northern coast for agricultural and municipal use (see Chapter 6). Depending on the rate of removal, measured in millions of cubic meters per day, this project is estimated to have a life of 100–500 years. The project is draining an aquifer that collected water between 38,000 and 14,000 years ago when the regional climate was humid, and it is not being replenished. This situation illustrates the unsustainable nature of groundwater development projects that permit extraction at rates that exceed recharge; the water is effectively a nonrenewable resource. This has brought to the fore two conundrums that were not evident in the 1950s: the trade-off of intergenerational equity for current consumption (Portney and Weyant 1999) and the question of what will happen to inflated populations dependent on unsustainable consumption when the water finally, inevitably, runs out (Postel et al. 1996).

19.6 Enhancing Water Supplies

Surface water development and management was an even greater preoccupation than groundwater in much of the world during the postwar years, and figured prominently in *The Future of Arid Lands*. Along with the general theme of water use "efficiency," the conferees considered the particular approaches of induced precipitation, water harvesting (as it is now known), desalination, and wastewater reuse.

19.6.1 Weather Modification

The idea of inducing precipitation by cloud seeding is seductive and reflects a brimming optimism and faith in technology. As Schaefer (1956) artfully expressed it, weather modification would allow the "... tapping of unlimited water from the sky rivers which flow over arid lands ..." and conferees discussed "experimental meteorology" for "utilizing water resources of the air." While schemes for weather modification often have been promulgated by charlatans and conmen for shady purposes, they were then and continue to be seriously undertaken by scientists and governments seeking to bring more water to drylands. High-altitude bombers retired from World War II made excellent platforms for cloud seeding experiments. In 1956, hope was still high that research would produce practical results in weather modification, but even advocates were beginning to recognize there might be no easy solution to the problem. In fact, 50 years later, deliberately inducing precipitation still has not proven feasible except in special circumstances in limited areas and is not considered a practical technique to pursue, but it still may have some value as a demonstration of good faith on the part of decision makers ("We are trying *everything!*"). By contrast, inadvertent weather modification by human activity seems to have been quite effective, as we now grapple with the effects of an atmosphere laden with greenhouse gases. Human-induced global climate change was not at all a concern in the postwar years (Ehrlich 2005), and its recognition today represents another significant psychological shift in thinking about water management (Calvin 1998).

19.6.2 Water Harvesting

Unlike the futuristic and fanciful weather modification approaches, water harvesting—primarily conducted at a small scale—for domestic and agricultural use has been practiced for millennia. Such techniques can be successful where the costs of "sacrifice" land and sufficient labor to maintain the infrastructure are low relative to the value of the harvested water and its produce. From 200 BC to 700 AD, for example, the Nabateans maintained large-scale water harvesting systems supporting settlements in the Negev Desert and the Arabian Peninsula, on the fringes of the Roman and Byzantine empires. These systems acted as critical links for supporting caravans traveling along trade routes. The value of these settlements to commerce justified the substantial investment in land and labor needed to construct and maintain large water harvesting systems. However, when trade flows diminished or new routes were opened, these systems were ultimately abandoned (Rubin 1991). Although water harvesting has been of continuing interest in drylands, with few exceptions[5] it remains practicable only on a small scale (with catchments of about 100 m^2 or less) and is most common in traditional or isolated settings. Certainly, over the last 50 years large-scale industrial water harvesting systems have not proven economically viable, due primarily to the cost of labor (Dutt et al. 1981; Tabor 1995).

19.6.3 Desalination

Desalination of seawater or brackish water to provide an abundant supply of potable water for desert cities was a grand hope in the 1950s, and again was viewed simply as a straightforward technological challenge (Krul 1956). Obstacles to the two primary approaches considered—thermal distillation and reverse osmosis using a membrane differentially permeable to water and salts—included inadequate available technology, complexity, and energy cost. Energy was relatively cheaper in the 1950s than it is today, but distillation and membrane technology were less energy efficient. Even in the 1950s, alternative energy sources such as solar, wind, and geothermal energy were considered in conjunction with desalination, though this was a comparatively new concept (Powell 1956).

In spite of these obstacles, and although slower than had been hoped, great progress has been made in desalination since large-scale operations began in Kuwait in 1957 (Hamoda 2001). Due to advances in membrane technology, reverse osmosis under pressure is now the low-energy method of choice. The world's largest desalination plant, in Ashkelon, Israel, is currently producing 275,000 m^3 of freshwater per day at 3.85 kWh of electricity per cubic meter (kWh/m^3). A demonstration plant in San Leandro, California (USA), operates at less than 2 kWh/m^3 and is working to reduce this to 1.5 kWh/m^3. For comparison, the electricity required to process *freshwater* by California's State Water Project averages about 2.5 kWh/m^3, and the Colorado River Aqueduct Project needs about 1.6 kWh/m^3 (Smil 2008).

There are now about 12,500 industrial-scale desalination plants in operation worldwide (see Chapters 6 and 15); about half of the global capacity is in the Persian Gulf region, where desalination meets 40–80% of total freshwater needs (Ettouney et al. 2002). As technology has improved in efficiency, the cost of desalination in constant dollars has fallen from about US\$6/m^3 to as little as US\$1/m^3 for seawater, and US\$0.50/m^3 for brackish water (FAO 2005). Still, desalination remains too expensive for agricultural use in all but a few instances (e.g., off-season greenhouse tomato production for export in Spain) and remains viable for municipal use only, particularly where population is concentrated, saline or brackish water is freely available, and other sources of freshwater are limited or distant (FAO 2005). In addition, the extreme fluctuation in the price of petroleum, which rose precipitously (to almost $150/barrel) before declining even more drastically (to about $50/barrel) in 2008, introduces unacceptable uncertainty and impedes innovation in this sector. As in 1956, maintenance and energy costs remain the largest obstacles to wider use of desalination, and today additional new challenges are becoming evident: purifying polluted source water and disposing of brines (possibly toxic) in a benign way. The niche that desalination can occupy appears to be narrower than might have been imagined 50 years ago (Hutchinson and Herrmann 2008).

19.6.4 Wastewater Reuse

Only one paper in *The Future of Arid Lands* dealt with wastewater reuse, and although it was mentioned elsewhere in the volume, it was not given nearly the emphasis of new source development. The need to manage agricultural and municipal effluent as a resource was weakly acknowledged, but water reuse wasn't considered as an element of an integrated dryland water management system, and it wasn't thought of as a large-volume contributor to meeting water needs. However, this neglect by the 1955 conferees was not completely representative of general opinion among municipal water managers and others. By the 1950s wastewater treatment was a major activity, and as the aggregate cost of treating larger volumes of effluent rose, and the purity of the product improved, it made economic and practical sense in drylands to reuse wastewater for agriculture, recouping some of the cost of treatment and offering a local supply of water to agribusiness.

Since about 1960, the reuse of wastewater has spread rapidly and has become an established management practice. Today, treated municipal wastewater plays a significant role, or several roles, in the water budgets of many arid land cities around the world (Scott et al. 2000). In addition to supporting peri-urban agriculture, it is widely used for urban landscaping irrigation, particularly on golf courses and other turf facilities. Other common uses include recreational surface-water impoundments, wildlife habitat rehabilitation, and groundwater recharge.

A more extreme example of effluent reuse is in the city of Windhoek in Namibia, southern Africa's most arid country. Since 1968 Windhoek has recycled virtually all of its urban wastewater for reuse as drinking water. This practice has been considered a successful way of dealing with unusually severe water limitations (Haarhoff and Van der Merwe 1996; Lahnsteiner and Lempert 2007). Worldwide, only about 35% of wastewater is treated (and nearly none reused for any purpose), and most of this occurs in developed countries. In developing countries, the use of untreated effluent for agriculture around cities is common and growing (Scott et al. 2004), despite the potential health risks it poses from bacteria, parasites, heavy metals, and other hazards. Even in rich countries, the beneficial use of wastewater has recently been complicated by the recognition of "emerging contaminants" such as endocrine-disrupting compounds remaining in the treated output that can be deleterious to living organisms, including humans. However, it is becoming harder to ignore wastewater as a resource in drylands given the realities of limited primary water supplies, the continuous and growing wastewater streams, and the increasingly attractive economics of peri-urban agriculture as transport costs rocket and the sensibility for "eating local" revives. The development of low-cost, effective treatment techniques is likely to intensify in arid lands to allow more widespread use of wastewater resources.

19.6.5 Stormwater Runoff

Stormwater runoff from impervious surfaces in urban environments was not mentioned in *The Future of Arid Lands*, either as a resource or a disposal problem. In recent decades, as cities have grown in size, density, and impervious surface area, it has become recognized as a water quality issue to be addressed and as a driver of some adverse downstream physical impacts (National Academy of Science 2008). Very recently, in arid lands, it has been viewed as a potential water resource (Hatt et al. 2006). Small-scale household use of runoff from rooftops and courtyards, practiced for millennia, is better thought of as a form of water harvesting, while stormwater use in our context is distinguished by its larger scale and essentially urban setting. In this setting, the quality of stormwater runoff can be poor because it collects automotive and industrial pollutants as it drains from roadways and dusty rooftops. However, calculations of the quantity of potentially usable, local stormwater are displacing this disincentive to exploitation. An Australian study found that the average annual urban stormwater runoff was almost equal to average annual water use in some cities (Hatt et al. 2006). The city of Santa Fe, New Mexico (USA), has calculated that, hypothetically, collecting its annual average 14 inches of rainfall from the 23,885 acres within city limits would provide 27,945 af of water, more than twice the current consumption of 13,000 af (City of Santa Fe 2002). While recent arguments have been made for more focused and deliberate management of stormwater as a resource, treatment and best practices for integrated management have yet to be worked out, so use of urban stormwater remains a potential tactic (Hutchinson and Herrmann 2008).

19.6.6 Conservation

In the literature from the postwar period, the concept of "water conservation" in arid lands is evident in the physiological sense of water conservation by desert-adapted animals and plants and in the sense of reclamation, or impounding water to prevent its "waste" by flowing into the sea unexploited. But water conservation in the sense of applying technology and modifying behavior to reduce water consumption was barely visible; it was not considered as a tactic in *The Future of Arid Lands*. Fifty years later, personal, household, and municipal water conservation in arid and drought-prone areas is very much in evidence as an important, cost-effective strategy for making better use of available supply to provide for some additional growth or establish the sustainability of water-limited systems. Less visible to most people, but potentially of greater magnitude, are conservation practices implemented to reduce the approximately 70% share of total water use in many regions allocated to agriculture. Drip irrigation, plastic mulches, greenhouse agriculture, and other conservation tools are used in drylands where the cost of water has risen enough to justify infrastructure investment and drive adoption. Where water is treated as a public good, policy has rarely been to charge users a price that would encourage conservation, and partial privatization of water utilities is changing that only slowly. As a result, cost has not been as strong a driver of conservation as it could be. In some places, drought, limited supply, and threatened or enforced rationing have been sharper goads to conservation.

19.7 Water Allocation Policies

In the postwar period, modes of water management reflected the strongly centralized, tightly closed, highly technocratic, and diplomacy-driven paradigms of decision making that prevailed generally throughout the West, its Soviet counterpart, and the postcolonial developing world (Milich and Varady 1999). Domestic water allocation mechanisms as well as international transboundary procedures adhered to this generally top-down model. In keeping with the paramount role of the state that emerged after World War II, this form of management, which left little voice to users and those affected by government policy, was largely unchallenged.

But by the late 1950s, these centralized forms of management were being displaced slowly by increasingly popular rational-actor models. Such models featured a reduced role for government in decision making, and by the 1970s the noncommunist world began a long retreat from state-centered planning and policy in most realms of administration. Water allocation was subject to this trend, and like other sectors of the economy, felt the force of structural allocation and neoliberal economics. But not until the fall of communism and the advent of the concept of sustainability—both in the late 1980s—did water management across the globe begin to modify its past approaches (Varady et al. 2008b).

By the early 1990s, and especially after the influential 1987 Brundtland Report (Our Common Future) and the 1992 UN Conference on Environment and Development in Brazil, the concept of sustainability—that is, the notion that responsible stewardship of the planet and its resources should constrain development—began to take hold. During that period, following on the successes of the environmental movement in the US and Western Europe in the 1970s, nongovernmental organizations (NGOs) began to participate in and influence environmental decision making by demanding a greater voice in determining how, how much, and to whom water should be allocated. Accompanying this reconfiguration of the closed, top-down decision-making model for water management was a new awareness of the importance of such issues as access to potable water and sewerage, equity, use of appropriate technology, allocations of water for recreational and environmental purposes, upper-basin/lower-basin conflicts, the integration of science and management, and the gradual awareness of the centrality of conservation.

The intertwined subjects of water use efficiency and allocation among sectors were discussed in *The Future of Arid Lands* and even picked up by contemporary reviewers of the book, but the treatment was from a delimited, engineering point of view and lacked the urgency the subjects are taking on today. Koenig's (1956) logical yet provocative premise was that irrigating drylands for agriculture was not an efficient use of water compared to using limited water supplies for cities and industry. For best efficiency on a continental or global scale, agriculture should be practiced only in more mesic regions, and in drylands water should be allocated to urban uses. Goods could be exchanged as needed "in these days of relatively abundant transportation." This point of view foreshadowed Allan's (1997) development of the concept of virtual water, which explicitly recognizes that water, in surprisingly large quantities, is embedded in the production and trade of essentially all food and consumer products, so people consume water not only directly by drinking or bathing, but virtually by consuming food and goods of all kinds (see Chapter 7). In the late 1950s, a countervailing argument to Koenig's ideas was that irrigation in arid lands could be made acceptably efficient and could provide a positive return on investment from the production of food and fiber, so that "one major justification for irrigation is the contribution it makes to the wealth of the nation" (McClellan 1956). In other words, using water to irrigate dryland crops may not be the most efficient use of the resource but is efficient enough to be profitable, so why not continue? Amid the optimism and abundance of the 1950s, both points of view could be fairly accepted, and there was little incentive to stop irrigating and move any nation's agriculture to well-watered areas.

Then, as now, there was recognition of the large differences among sectors (agriculture, industry, municipal) in their demand for water, allowable water quality, and their ability to pay. However, this understanding did not immediately prompt a concerted effort to address efficiencies among sectors, how they might respond to differences in price, or adjustments that might be made on the demand side of the equation. The notion of water markets or the mechanism by which each of these sectors might compete for a scarce resource was not reflected in the general tenor of the book. Instead, the general belief seems to have been that the greatest advances would come on the supply side rather than the demand side of the water balance equation (Hutchinson and Herrmann 2008).

Since the immediate postwar years, water rights and water markets have evolved, and, particularly in regions perceiving limits to supply, shifts in water valuations have driven changes in the allocation of water among sectors. The general flow of water has been toward cities or, more colorfully, "uphill toward money" (Reisner 1986). This has happened on a large scale through massive public water projects, including interbasin transfers. Purchases of local agricultural land by cities to secure water rights are becoming more common. These measures may give an illusion of sustainability, but they seem to represent a transitional state in the thinking and practice of water use efficiency and allocation. The competition among public and private interests and the regulatory environment are complicated and still evolving, so the subject is fraught. But water markets cannot simply allocate to the highest bidders, desiccating less-affluent communities—human and biotic—and urban populations will continue to rely on agricultural production, which in all likelihood will be more secure the more local it is. Water use and allocation at the limits of supply still hold considerable uncertainty.

19.8 Toward Integrated, Global Water Management

Water governance used to be thought of as a purely national activity, undertaken by the central state or in some cases by regional governments. Prompted partly by complex international, transboundary water-management challenges, new forms of governance emerged in the 1980s that began transcending national borders. At first characterized by river basin commissions and authorities, these new forms of transnational management began to exhibit an ever more comprehensive frame of reference.

Difficult obstacles to water management, such as drought, flooding, contamination, and loss of biodiversity have led decision makers to seek solutions across political borders (Conca 2006; Wolf et al. 2003). International cooperation has yielded treaties, compacts, and formal and informal agreements, governing large multinational watersheds such as the Senegal and La Plata river basins and small catchments such as the San Pedro River basin in the US–Mexico border region (Postel and Richter 2003).

Water management has become more eclectic in the face of a larger set of challenges, and the reach of governance has extended beyond regional schemes to include globally conceived organizations that focus on integrated water resources management, termed "global water initiatives" (GWIs). They include (1) professional scientific societies such as the International Association of Hydrological Sciences and the International Water Resources Association, (2) designated time periods such as the International Hydrological Decade (1965–1974) and the International Water for Life Decade (2005–2015), (3) organized events such as the 1992 Dublin International Conference on Water and Environment and the triennial World Water Forum, and (4) issue-oriented organizations including the UN-affiliated, intergovernmental International Hydrological Programme, the non-governmental Global Water Partnership, and the World Water Council (Varady et al. 2008a).

These GWIs hail a perceptible if gradual shift in water governance from a mode in which policy changes by way of relatively isolated actions that affect local management and environments, toward a decentralized type of water management featuring global-level precepts (such as sustainability, equity, access, public participation, integrated management, and the use of sound science) as well as formal governance mechanisms (e.g., empowerment of watershed councils, fair enforcement of quality and quantity regulations, development and maintenance of appropriate infrastructure, formation of policies and procedures that account for prevailing sociocultural practices and demographic changes, and application of current information and monitoring technology).

Such factors were hardly imagined by the attendees of the 1955 conferences and barely acknowledged by such a forward-looking and sage observer as Gilbert White, editor of the 1956 volume. Captives of the thinking of the times, they saw solutions in large, centrally administered, technology-driven, and generally uniform packages. If there wasn't enough water, we would "make" more. If its quality was insufficiently good, we would clean it. If water needed to be governed, the strong hand of the state would do it.

Now, in the post-post-World War II era, in the aftermath of the Cold War, and in the first decade of the new century, water scientists and water managers are rethinking the challenges and devising new forms of management. Like analogous trends toward global coordination in other sectors (such as human rights, the HIV/AIDS crisis, and global climate change), the move toward a benign form of global water governance is helping shape the contours of water knowledge, policy, and management through governance arrangements among states and outside the state.

Parallel to this shift in thinking has been a growing intellectual elaboration of an integrated water management paradigm, which recognizes that each element on both the supply side and the demand side of the equation makes a contribution to the total amount of water available, and requires consideration of linkages between urban and rural water use as well as between the domestic, industrial, and agricultural sectors. Moreover, water management thinking has moved from regional to global since the 1950s, with the emergence of the GWIs for world water governance (Varady et al. 2008b). Certainly, water management will continue to function at multiple scales and degrees of integration, and as yet the concrete effects of GWIs are hard to identify. But the trend is toward globalization of water management to achieve higher levels of integration.

While some GWIs date back decades, most are recent. Between 1995 and 2005, about two dozen such initiatives were established. This proliferation has actually been recognized as a problem in the ironically decentralized field of world water management, because it presents a challenge to coherent policy coordination and leads to duplication of institutional efforts and unnecessary competition among organizations for financial, social, and status-linked resources (Varady et al. 2008b). A further problem perceived both within GWIs and externally is the problem of imprecision—vague declarations and a pervasive lack of clarity, specificity, and quantifiable outcomes.

But not all is negative if the universe of GWIs is looked at as a network rather than a collection of independent actors. In this view, institutional diversity, multiple collaborations and overlapping functions are a means to work toward consensus and effective transboundary management of complex systems. Some consolidation may be warranted, but highly centralized control is not necessarily a feasible or desirable goal in water management. Despite a dearth of rigorously quantifiable objectives, GWIs are generally politically influential and well supported. They will likely persist as the enterprise of globalizing water management strengthens.

19.9 What Have We Learned About Water Management for the Twenty-First Century?

Contrasting what was known in the 1950s with what has been learned since should, at the very least, provide a healthy dose of caution, or at least modesty. Practically, we must acknowledge that we are now somewhere along a trajectory that may—or perhaps may not—extend far into the future. What, then, are the general trends that emerge?

First, we will continue to hold out for and actively pursue technical solutions that will meet the need for increasing amounts of fresh water, or working the supply side of the water budget. It seems certain that technologies like desalination will continue to advance, opening the vast stores of low quality water to higher value uses—just as was envisioned 50 years ago. However, implementation of many solutions will continue to be an ever-escalating game of "whack-a-mole"—knocking down a problem on one front causes another one to appear someplace else. For example, many of the water solutions that have been pursued in the past, such as transporting water over long distances, tapping non-replenishable water reserves that were put in place during other times (i.e., groundwater), or making water usable by removing impurities, all require considerable inputs of energy. Needless to say, expanding energy production has another whole set of constraints that will affect our ability to pursue a secure water future.

Second, while progress continues on the supply side, a great deal more success has been achieved in managing and balancing the demand side of the water budget. The former is driven almost exclusively by the physical sciences and the latter by the social sciences. Thus water management may provide one of the better examples of how the two basic facets of science can be brought together to address a major social challenge. Together, they drive us toward increasing efficiency and, we may hope, toward sustained productivity and equity among competing interests.

Along with the growing awareness that societal use of water is as important a factor as technical supply enhancement comes the realization that water management is a complex exercise requiring both scientific expertise and institutional appropriateness. Whereas past efforts paired engineering solutions with secretive, command-and-control water-management strategies, we are increasingly recognizing that water users themselves should participate openly in decision making that affects their access to water. For the most part, this shift in emphasis from centralized authority to greater public involvement has benefited from the work of NGOs and other global water initiatives. In short, at local, regional, and global scales, the role of diverse institutions in policy making has begun to supplant the influence of technocrats.

Next, we should expect the unexpected. At the very time that researchers were working futilely to control the weather in the mid-1950s, an observatory was constructed atop Mauna Loa in Hawaii (USA) that began to monitor atmospheric concentrations of carbon dioxide and thus chart how we were changing global climate without even knowing it. Few at the time could imagine the Pandora's box of connections that have spun out of those unwitting changes. First off, water management is based on the concept that we can know—in general terms—how much water will be available at some point in the future. This is the notion of stationarity—that the climate of the future will behave pretty much like it has in the past and that we can plan within an envelope of known variability. Stationarity was declared dead quite recently (Milly et al. 2008); without this guiding concept, we are sailing blindly into uncharted waters. How can we maintain an adequate global water supply without snowpack on the mountains? How can we enlarge our storage capacity to compensate? How do we allocate a dwindling resource among growing needs? How much additional water will be consumed during the growing season when it is two months longer? What about four months? How can we grow crops, control erosion, or store runoff if rainfall comes in three large storms during the growing season instead of eight small ones?

Finally, the continuing theme is that there are no single or simple solutions for provisioning adequate water supplies to arid lands. Initially, the scale of the problem was small, generally restricted to one or a group of neighboring communities. As our geographic reach grew as a function of the growth of our population and national economies, our purview expanded to include watersheds and regions of subcontinental scale. Now that our economy, environment, and climate are shared globally, the scale of both our challenges and the solutions to them has expanded to encompass the entire planet. Reconciliation of these problems will be achieved through incremental solutions to both the supply and demand sides, implemented on a variety of scales, in a host of different regions, under diverse management regimes, and via suitable institutions. No one has ever said this would be easy to accomplish.

Notes

1. To the question, "Why do you rob banks?" Sutton (1901–80) replied (famously but apocryphally, it turns out), "Because that's where the money is."
2. Thomas Malthus (1798) argued famously that growing populations would eventually outstrip the world's capacity to feed these populations. He was writing at a time when the global population was a small fraction of the current population and improvements in agricultural technology rendered his prophesy premature. Neo-Malthusianism has resurrected the thesis and proposed anew that food production will prove insufficient to feed all the world's people. Whether current conditions will lead to the predicted catastrophe is a subject of debate.
3. Many of these concerns prevail as well in developing nations.
4. Karl Wittfogel (1957), who postulated a theory of hydraulic societies, may be the best known of these writers.
5. For example, hillside runoff capture used by American Indian cultures such as the Tohono O'odham in the southwestern United States.

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Glossary of Units of Measurement and Chemical Formulas

Units of Measurement

ac	acre
af	acre-feet
cm	centimeter
ds/m	deciSiemens per meter
°C	degree Celsius
EC	electrical conductivity
Gt C/yr	gigaton of carbon per year
g	gram
gC/MJ	gram of carbon per mega joule
gC /m^2/yr	gram of carbon per meter square per year
g kg^{-1}	gram per kilogram
g/L	gram per liter
ha	hectare
hm^3	cubic hectometer
kg	kilogram
kg/m^3	kilogram per cubic meter
km	kilometer
km^2	square kilometer
km^3	cubic kilometer
L	liter
m	meter
m^2	square meter
m^3	cubic meter
m^3 a^{-1}	cubic meter per year
m^3 ha^{-1}	cubic meter per hectare
m^3/sec	cubic meter per second
m^3 t^{-1}	cubic meter per ton
mi^2	square mile
Mm^3	million cubic meters
μg/L	microgram per liter
μm	micrometer

G. Schneier-Madanes, M.-F. Courel (eds.), *Water and Sustainability in Arid Regions*,
DOI 10.1007/978-90-481-2776-4_BM2,

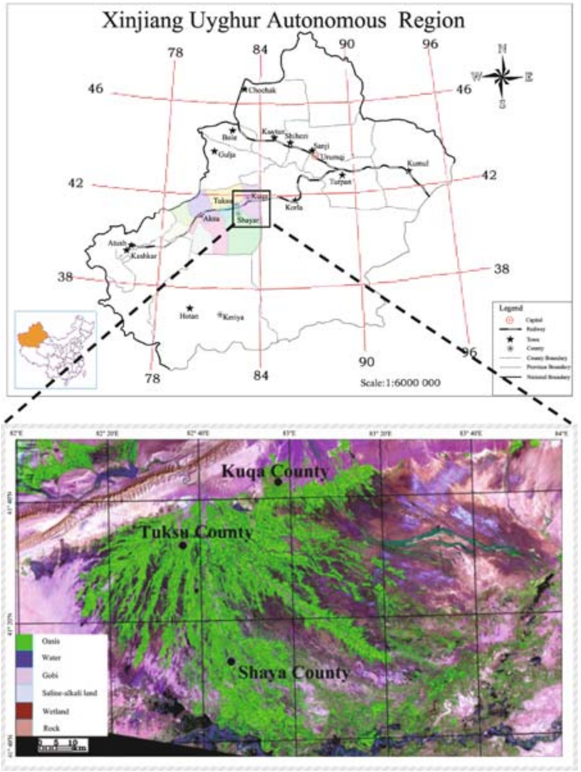
μmhos/cm	micromhos per centimeter
mi	mile
mg	milligram
mg/kg	milligram per kilogram
mg/L	milligrams per liter
mm	millimeter
Mha	million hectares
Mha y^{-1}	million hectares per year
Mt y^{-1}	metric ton per year
mon	month
Ngg^{-1}	nanogram per gram
sec	second
t	ton
yr	year

Chemical Formulas

Cl^-	chloride
F^-	fluoride
Fe^{+3}	iron (+3) cation
Mn^{+2}	manganese (+2) cation
NO_2^-	nitrite
NO_3^-	nitrate
PO_4^{-3}	phosphate
SO_4^{-2}	sulphate

Color Plates

Plate 1 Study area location. (See also Fig. 2.1 on p. 18)



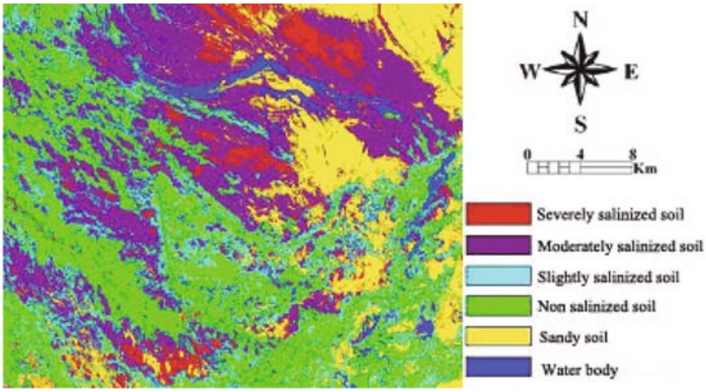


Plate 2 Soil saline levels. (See also Fig. 2.4 on p. 27)

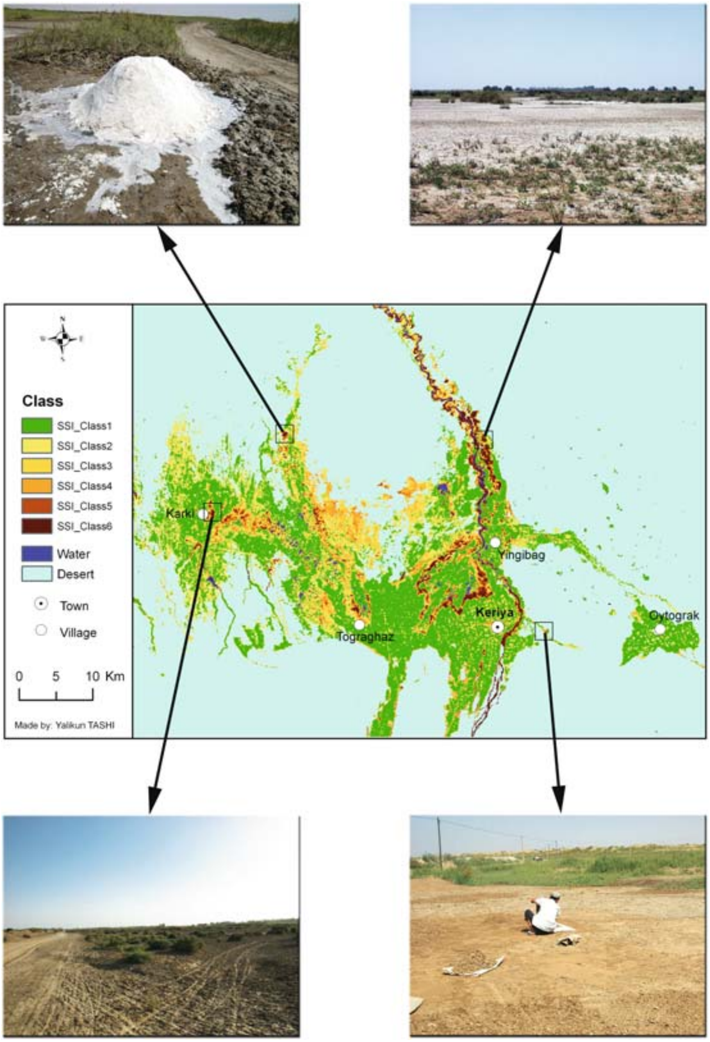


Plate 3 SSI (Soil Salinity Index) image calculated from the Landsat ETM+ image acquired on October 7, 2002, and photos showing the surface state of salt-affected soils in different parts of the study area. The class numbers correspond to the different degrees of salinity in ascending order. (See also Fig. 4.8 on p. 63)

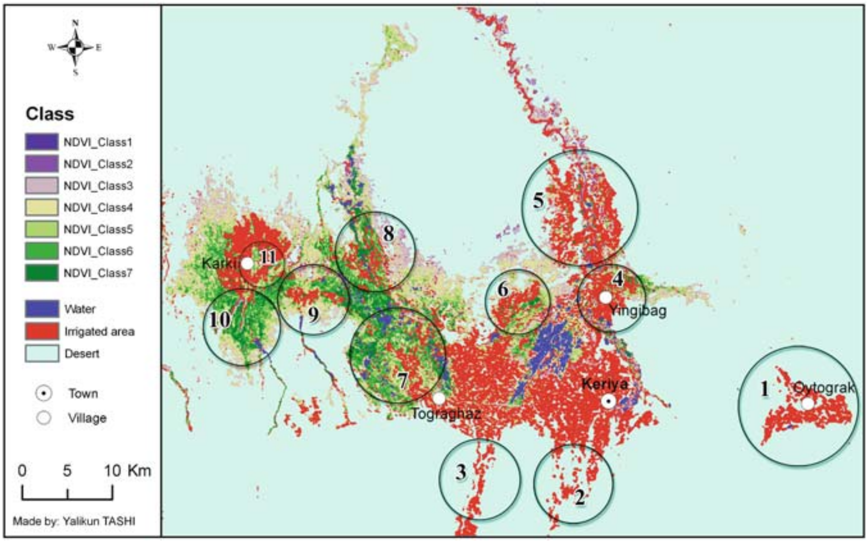


Plate 4 Classification image of Landsat MSS acquired on June 23, 1977. The classes from NDVI_class1 to NDVI_class7 were obtained by binning the NDVI values; higher class numbers indicate higher NDVI values and thus greater density and greenness of vegetation. (See also Fig. 4.9 on p. 66)

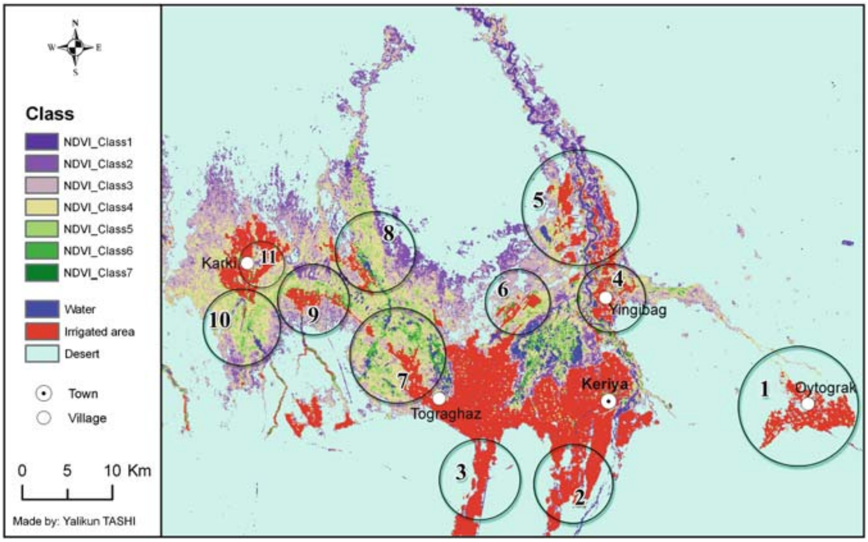


Plate 5 Classification image of Landsat TM acquired on October 17, 1991. The classes from NDVI_class1 to NDVI_class7 were obtained by binning the NDVI values; higher class numbers indicate higher NDVI values and thus greater density and greenness of vegetation. (See also Fig. 4.10 on p. 66)

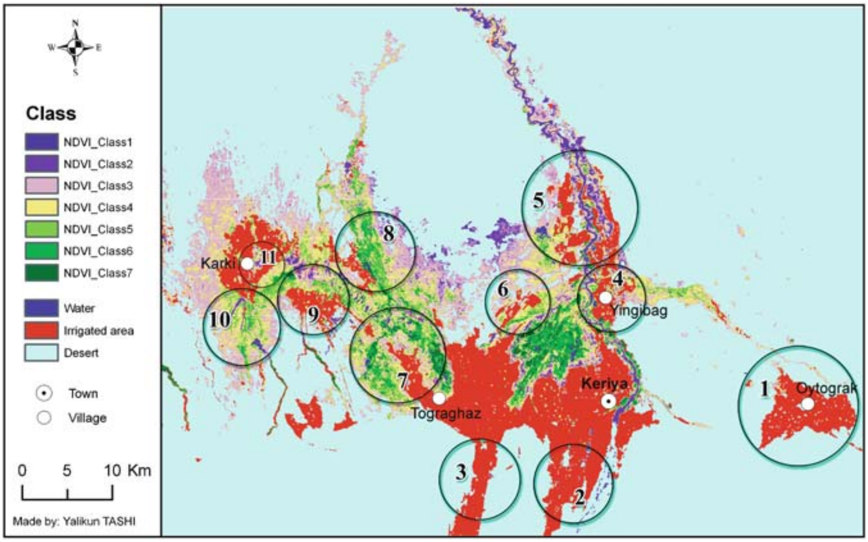


Plate 6 Classification image of Landsat ETM+ acquired on October 7, 2002. The classes from NDVI_class1 to NDVI_class7 were obtained by binning the NDVI values; higher class numbers indicate higher NDVI values and thus greater density and greenness of vegetation. (See also Fig. 4.11 on p. 67)

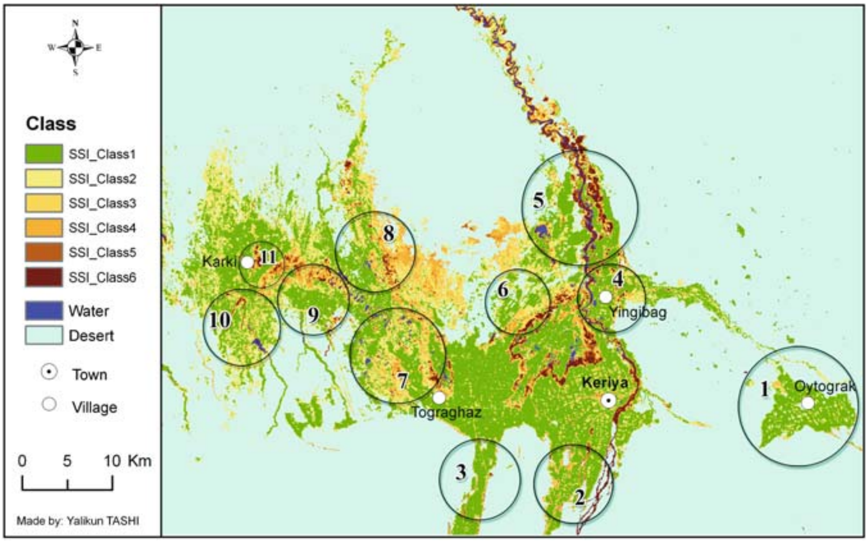


Plate 7 SSI (Soil Salinity Index) calculated from Landsat ETM+ image acquired on October 7, 2002. Class numbers correspond to different degrees of salinity in ascending order. (See also Fig. 4.12 on p. 67)

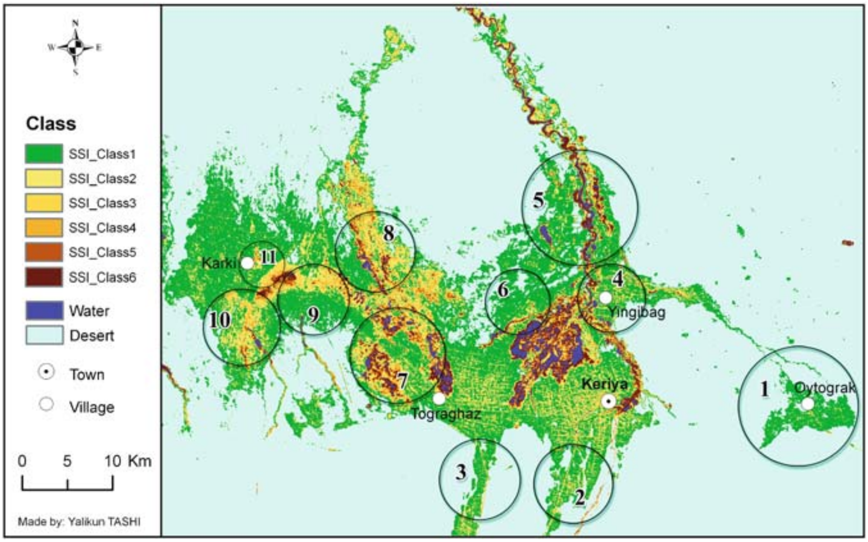


Plate 8 SSI (Soil Salinity Index) calculated from the image acquired on October 17, 1991. Class numbers correspond to the different degrees of salinity in ascending order. (See also Fig. 4.13 on p. 68)

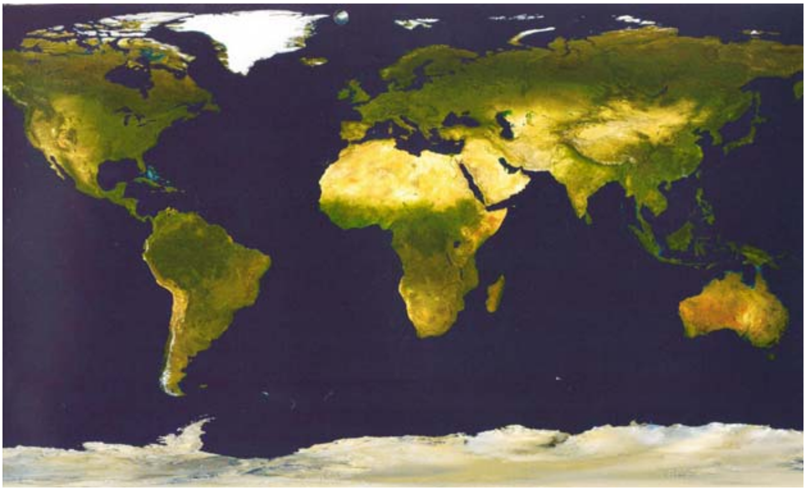


Plate 9 Dry areas of the world today (See also Fig. 7.5 on p. 111)

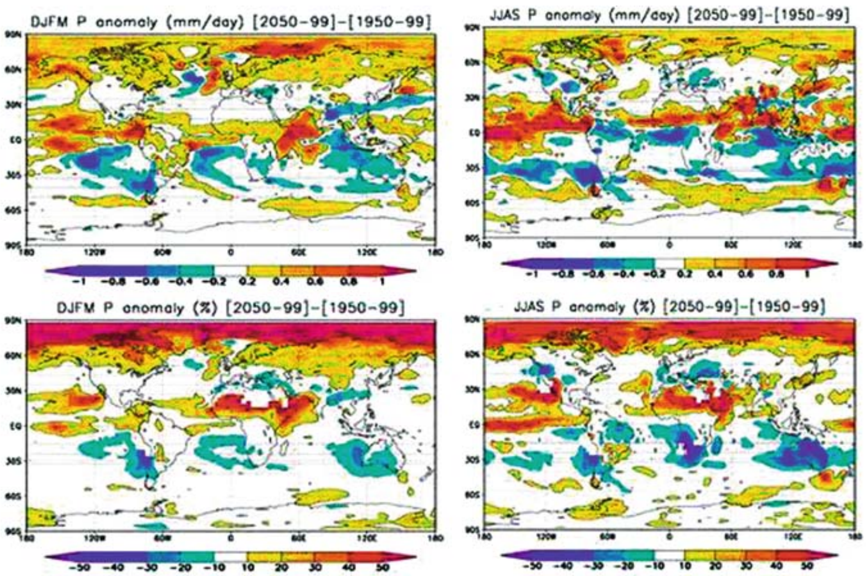


Plate 10 Precipitation anomalies (*top*: mm/day, *bottom*: %) calculated for the IPCC B2 scenario with the French CNRM model, comparing the averages for 1950–1999 and 2050–2099. *Left*: for December–March. *Right*: for June–September. (Source: Académie des Sciences 2006) (See also Fig. 7.6 on p. 112)

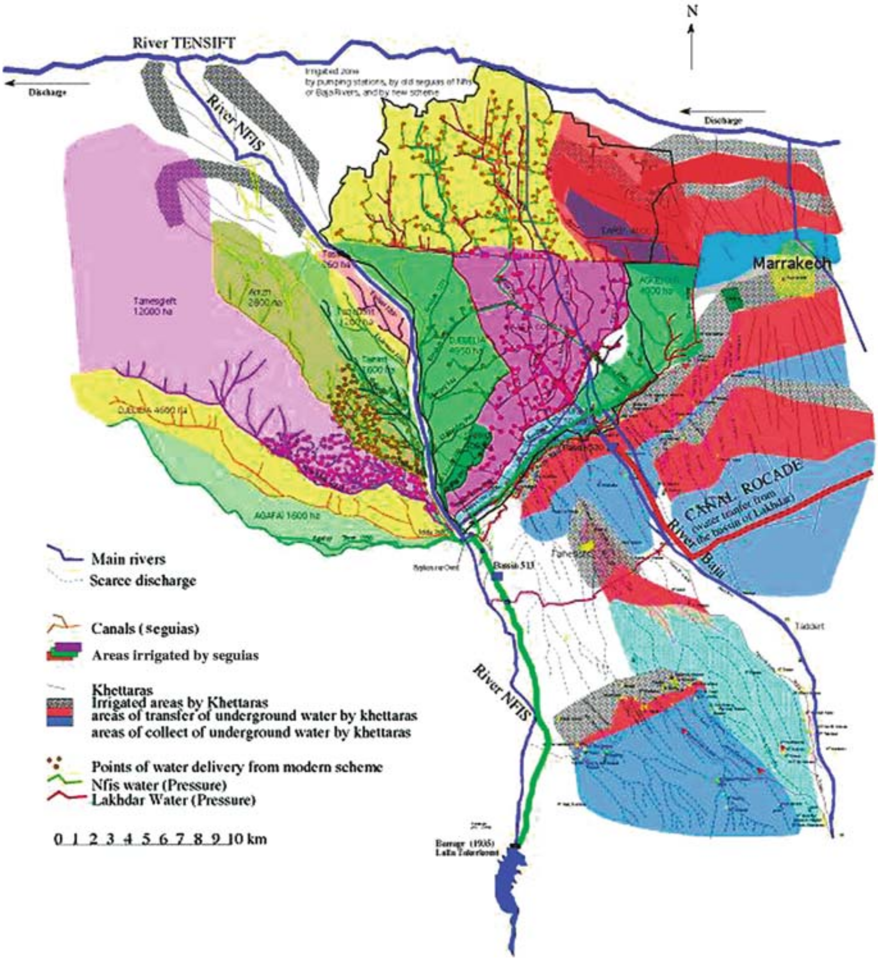


Plate 11 Organization of the khettaras in central Haouz, west Marrakech. (Most of the seguias still run, while most khettaras are out of order) (Source: ORMVA Archives) (See also Fig. 10.6 on p. 156)

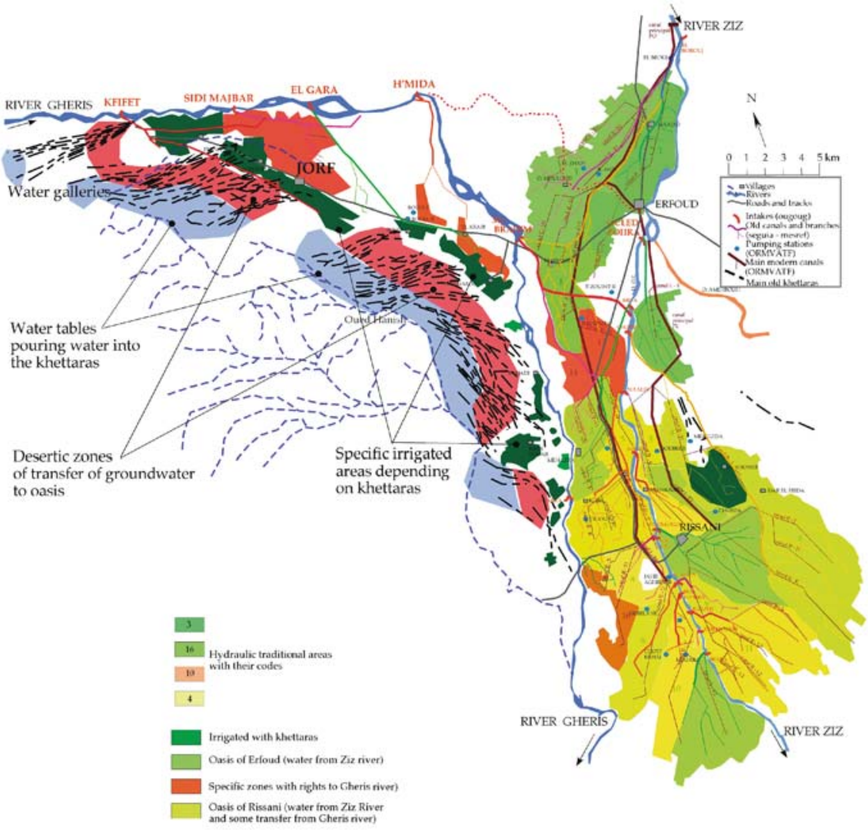
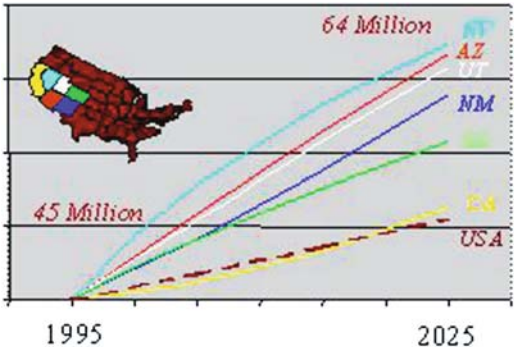


Plate 12 Organization of the khettaras in Tafilalet province. (Source: Thierry Ruf 2008, based on ORMVA-TF-SCET 1983. “Plan directeur de mise en valeur agricole du Tafilalet” Vol. No. 9, Rapport de synthèse) (See also Fig. 10.7 on p. 158)

Plate 13 Population growth rates in the Southwest US (See also Fig. 14.1 on p. 222)



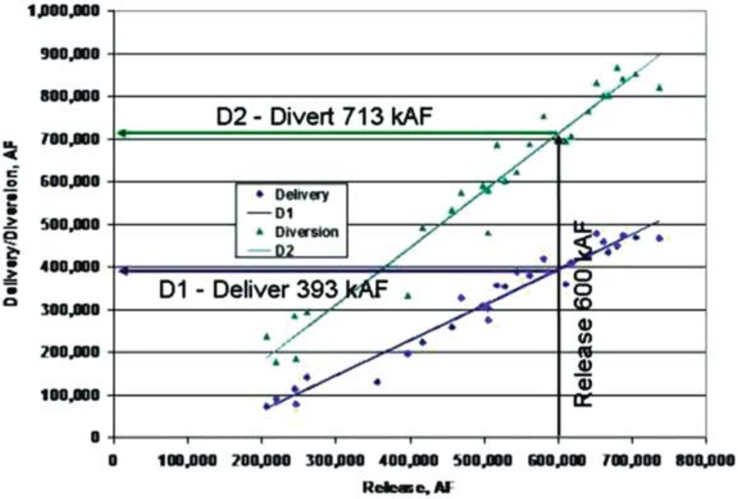


Plate 14 The D1 and D2 curves used by the Rio Grande project (See also Fig. 14.6 on p. 233)

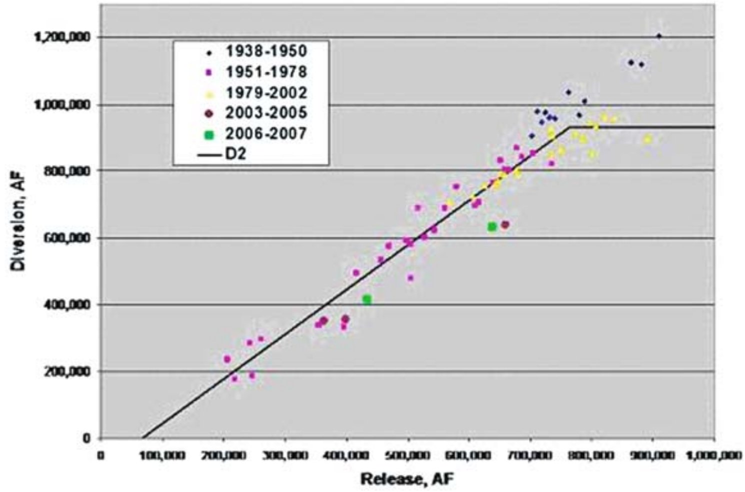


Plate 15 Visualizing groundwater pumping impacts (See also Fig. 14.7 on p. 235)

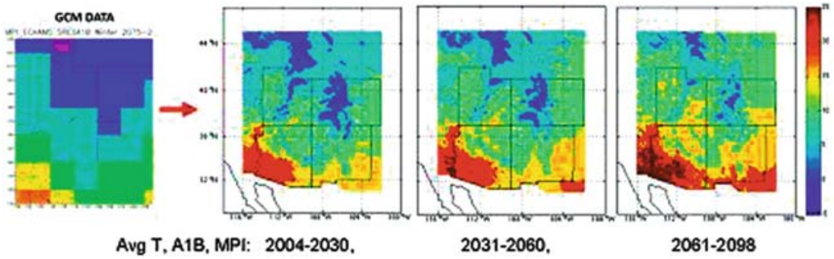


Plate 16 Example of downscaled GCM projections for the US Southwest. The map to the *left* represents data at the GCM resolution. (Source: Cañon et al. 2008a) (See also Fig. 14.12 on p. 241)

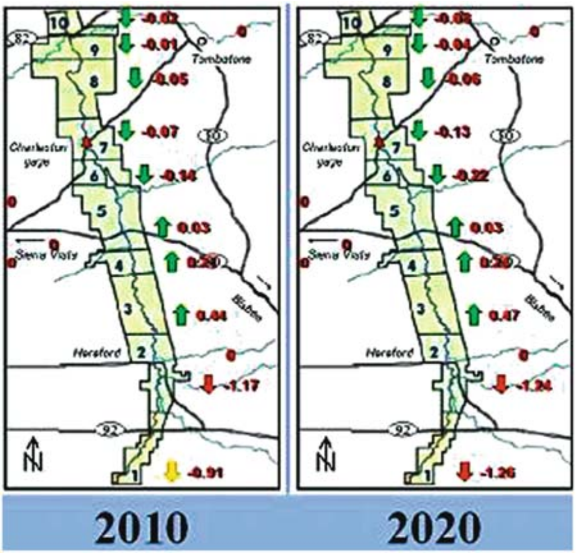


Plate 17 DSS results for 2010 and 2020 development scenarios. *The arrows* indicate the direction of change in riparian groundwater levels; the *color of arrows* indicates the magnitude of change. *Red* represents greater change, and *green* represents smaller change. (Source: Kang et al. 2009) (See also Fig. 14.13 on p. 241)

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