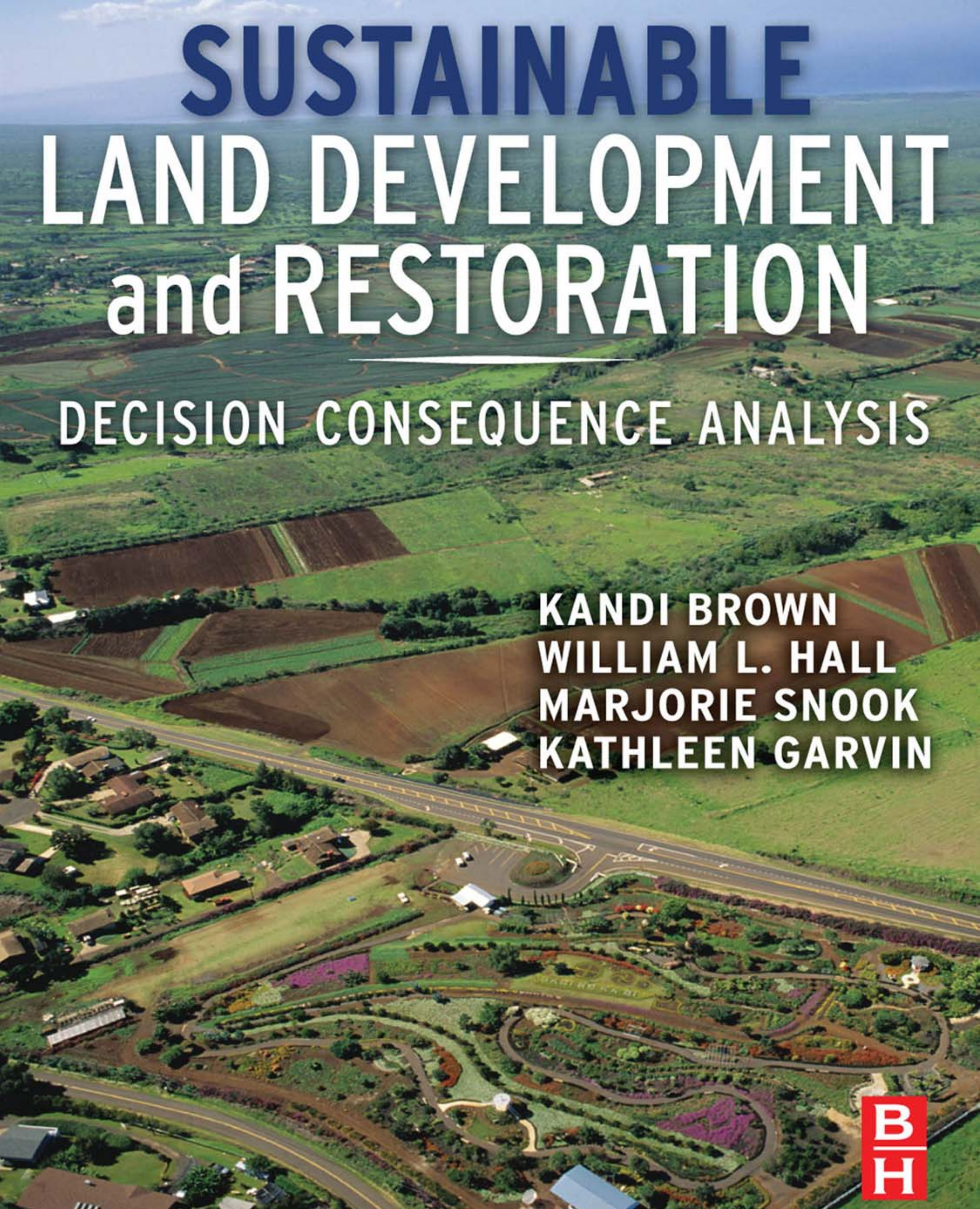

SUSTAINABLE LAND DEVELOPMENT and RESTORATION

DECISION CONSEQUENCE ANALYSIS

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Sustainable Land Development and Restoration

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Decision Consequence Analysis

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Butterworth-Heinemann is an imprint of Elsevier

Butterworth–Heinemann is an imprint of Elsevier
30 Corporate Drive, Suite 400
Burlington, MA 01803, USA

The Boulevard, Langford Lane
Kidlington, Oxford, OX5 1GB, UK

Library of Congress Cataloging-in-Publication Data
Brown, Kandi.
Sustainable land development: decision consequence analysis / Kandi Brown, William L. Hall, and contributors.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-85617-797-9 (alk. paper)
1. Land use—Environmental aspects. 2. Sustainable development. I. Hall, William L. II. Title.
HD108.3.B76 2010
333.73'15–dc22 2009040254

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

For information on all Butterworth–Heinemann publications visit our Web site at *www.elsevierdirect.com*

Printed in the United States
10 11 12 13 14 10 9 8 7 6 5 4 3 2 1

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Preface

This book, *Sustainable Land Development and Restoration: Decision Consequence Analysis*, provides a toolbox for both the novice and experienced practitioner to balance economic, environmental, and social assets and liabilities to the benefit of clients, property owners, and the communities within which we live. Throughout, techniques and case studies are presented that promote and demonstrate restoration and site development activities that provide measurable benefits on a global scale and do not simply represent an acute local expenditure of resources. The goal is to demonstrate that through multidimensional resource management analysis and practices, companies and societies can maintain sustainability within a balanced environmental system.

Descriptions of technical, contracting, and implementation processes are supported by detailed case studies to provide real-world contexts rather than just an academic exchange of theories.

Decision Consequence Analysis (DCA) is employed throughout this book as the lynchpin methodology. DCA structures multiple technical and psychological approaches into one comprehensive, unbiased decision-making framework. Consistent employment of DCA during the land development and restoration process can reduce decibel-driven, agenda-laden decision making; streamline expenditure of resources; and provide a clear path to the sustainable maintenance of balanced environmental systems.

This book is organized into five primary parts that take the reader from (1) an introduction to the national and international regulatory structure within which we operate; to (2) the foundation and application of DCA; to (3) state-of-the-art technical tools supporting DCA; through (4) employment of facilitation and mediation tools supporting decision implementation; and, ultimately, to (5) the combination of all techniques to enhance the triple bottom line associated with an entire portfolio.

The unifying theme of *Sustainable Land Development and Restoration: Decision Consequence Analysis* is achieving sustainability by creating human systems that have efficient feedback and response mechanisms. These mechanisms require accurate and relevant data, the capacity for decision makers to process and understand the data efficiently, and the capacity for decision makers to quantify (within the bounds of available knowledge and data) the limits of the consequences of the options for responding to environmental stimuli.

The chapters in Part I, "Introduction," set the framework of the book with a discussion of the current regulatory environment within which we operate and the potential for altering that framework through implementation of more advanced ecological economics. The impacts of the regulatory environment on a local and international basis are explored, as well as many of the legal driving functions forcing change within the private and governmental sectors.

The basic components discussed in the chapters of Part II, “Decision Consequence Analysis,” provide a review of the techniques and tools available for developing a factual foundation for evaluating a decision. Decision making is often dominated not by a holistic understanding of the facts but by anecdote, the memorable, or the anomaly; therefore, the most basic need is data fluency on the part of all the critical stakeholders. Data fluency promotes rational decision making within the context of the facts being considered as opposed to the irrational and potentially dangerous decision making that often plagues environmental and development decisions made in highly uncertain situations. This section describes the components needed for structuring a formal decision analysis. Its foundation is accurately defining your problem statement and clearly vetting your objectives to build a structure for the meaningful analysis of data.

Full-spectrum and value-added technical approaches to data collection and management, statistical analysis, forensics analysis, and risk assessment techniques are presented in Part III, “Tools for Sustainability Decision Making,” and explored through case history analysis. Case histories demonstrate how, when the data-driven decision-making framework is in place, you can construct a comprehensive DCA model with performance metrics to analyze alternatives and uncertainty—leading you to an informed, sustainable decision.

Elucidating the best path forward through DCA is only one component of addressing the full scope of issues faced in today’s economy. Systems are ultimately governed by people; therefore, Part IV, “Decision Implementation,” describes the people process. This section discusses the role of facilitation through analysis of traditional facilitation techniques and the development and implementation of technical facilitation techniques such as Decision-Based Partnering and Facilitated DCA®. The connections among contract development, technical performance, and facilitation techniques are explored through case studies.

In the chapters in Part V, “Sustainable Liability Management,” techniques, such as Portfolio Risk Management Analysis® and triple bottom line accounting, are presented as ways to advance environmental restoration from a shortsighted and localized activity to a sustainable and globally focused endeavor. These techniques may be applied in both the public and private sectors.

To clarify the information presented, all of the figures provided in this book are also available in color at *www.NewFields.com*—click on Publications.

List of Contributors

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Mr. Barrett earned a B.A. in architecture from Virginia Tech, an M.S. in public administration from the University of Southern California, and an M.A. in national security and strategic studies from the College of Naval Warfare. He has also attended the Kellogg School of Management, Northwestern University, and the Maxwell School of Government at Syracuse University. He is currently the chief of the Asset Management Division, Directorate of Installations and Mission Support, Headquarters, Air Combat Command at Langley Air Force Base in Virginia. Robert is responsible for all asset management affairs at Air Combat Command's 15 major installations and at smaller units in the continental United States. His principal responsibilities include real estate, real property, family housing privatization, operations and management, environmental policy, analysis, and compliance; installation restoration; environmental management, oversight, and training; and pollution prevention.

Kandi Brown, **NewFields**

Ms. Brown earned a B.S. in biology from Tennessee Technological University and an M.S. in microbiology from Eastern New Mexico University. Her graduate studies include civil mediation and civil engineering. She is a Rule 31 Listed Mediator in Tennessee and is on the Environmental Conflict Resolution Center roster. Kandi is a skilled communicator who helps clients understand technical, portfolio management and sustainability issues, and building consensus before taking sensible actions. Using Decision Consequence Analysis, she helps clients assess the impact of uncertainty on the value of real estate and infrastructure assets. At NewFields, Kandi has secured trademarks for Facilitated Decision Consequence Analysis and Portfolio Risk Management Analysis, and she has developed Decision Based Partnering. Kandi has assisted the U.S. Air Force on projects from individual sites to portfolio-wide evaluations. She led the development of the Sustainable Asset Accounting System™—a triple bottom line accounting system that supports advanced resource leveraging.

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Sam received his Juris Doctor in 1982 from the University of Georgia Law School, having earlier earned a B.S. in physics and mathematics from East Carolina University. Sam has developed strategies, conducted policy research, and led campaigns on numerous environmental issues, including clean energy, acid rain, climate change, wetlands protection, water quality and quantity, endangered species habitats, parks acquisition, urban forestry, and electoral politics. Sam was a lead negotiator for the Sierra Club in a campaign to protect the Okefenokee National Wildlife Refuge, which led to the DuPont Corporation's donation of the largest land conservation gift in Georgia history. Sam is a frequent guest lecturer in college courses on ecological economics and climate stabilization strategies. Sam has authored papers on regional management of water resources and biofuels and agricultural water use for the Georgia Water Planning & Policy Center.

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Ms. Duley earned a B.Eng. in chemical engineering from the University of Minnesota Institute of Technology and is a licensed professional engineer in Minnesota. She is an experienced environmental engineer and remediation professional with expertise in the design, implementation, and optimization of remedial solutions. She has used her communication, negotiation, and strategy development skills to support teams' navigations through complex projects. As a project manager, Megan has headed environmental restoration, environmental compliance, and munitions response projects for the U.S. Department of Defense, as well as for multiple state programs and private sector clients.

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Mr. Emsbo-Mattingly earned a B.A. in biology from Oberlin College and an M.S. in environmental science from the University of Massachusetts. He specializes in the diagnostic measurement of tar, wood preservatives, PCBs, petroleum, and industrial products in water, soil, sediment, and air. Stephen has extensive experience in manufactured gas plants, chemical plants, wood treating facilities, tar refineries, petroleum storage facilities, chlorinated solvent industries, and urban background. During his 20 years in the environmental industry, Stephen has helped pioneer forensic methods for tars, PCBs, and vapor intrusion investigations. During the course of his forensic investigations, he conducted detailed laboratory data reviews, quality control assessments, statistical analyses, and expert testimony.

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Ms. Garvin received a B.S. in biological life sciences from Clemson University in 1997 and an M.S. in earth and environmental resource management, with a focus in international environmental policy, from the University of South Carolina in 2002. Since that time, she has worked as an environmental professional with technical expertise in NEPA compliant environmental assessment, human health and ecological risk assessment, information management, and quality assurance. She is an AICP certified planner and currently supports the NewFields U.S. Air Force clients as an environmental planner, facilitator, and GIS analyst.

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Mr. Gobb graduated from the University of Oklahoma with a B.S. in petroleum engineering and is a licensed professional engineer in Texas and Oklahoma. He has more than 22 years of environmental engineering and consulting experience. He helps clients to analyze current and historic site data and explore options that meet regulatory obligation while streamlining the project and reducing overall project liabilities. Patrick's specialties include the performance of due diligence investigations (including environmental liability assessments), RI/FS, environmental compliance, risk assessments, soil and groundwater remediation system design and installation, regulatory interaction, and strategic analysis/guidance on Superfund sites. Patrick supports the evaluation and tracking of the U.S. Air Force Portfolio.

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Mr. Hall graduated from the Georgia Institute of Technology with a B.S. in civil engineering and is a licensed engineer in Georgia and Alabama. He has 35 years of experience managing multidisciplinary environmental projects, with expertise ranging from strategic planning to detailed process and civil design/construction management. Over the past 20 years, William has specialized in the application of decision theory for managing complex environmental liability portfolios in the public, private, and NGO sectors. William pioneered a decision theory method that has been used on more than one thousand sites worldwide at both the project-specific and portfolio-wide levels.

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Mr. Hayward received a B.S. in geology from New England College and an M.S. in marine science from the University of Florida. During his 30-year career, Gary has managed and directed a wide range of large multidisciplinary environmental programs throughout the United States and around the world. His specialties include environmental impact assessments, environmental siting and planning, and associated environmental permitting and regulatory compliance services for private and public clients. Categories include oil and gas pipelines, oil field development areas, and terminal and distribution facilities. Since 2000, Gary has also been involved in a wide range of environmental studies for the National Park Service at Yosemite National Park.

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Ms. Snook earned a B.A. in English in 2000 and later worked as a reporter for the *Marietta Daily Journal.* In 2004, she earned an M.S. in library science from the University of Illinois at Urbana-Champaign. After a brief stint in the news library of National Public Radio in Washington, D.C., Marjorie accepted a librarian position at NewFields. She assists engineers in conducting research on a wide variety of environmentally related topics and has helped to draft and edit a variety of technical documents intended for public consumption from litigation-related expert reports to the State of Georgia's Statewide Comprehensive Water Plan.

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PART

Introduction

I

Kandi Brown

Part I, "Introduction," sets the framework for this book with a discussion of the current regulatory environment within which we operate and the potential for altering that framework through implementation of more advanced ecological economics. The impacts of the regulatory environment on a local and international basis are explored, as well as many of the legal drivers forcing change within private and governmental sectors.

Chapter 1 discusses the international regulatory, social, and political framework for sustainable land development and restoration. Chapter 2 takes a look at existing policies, metrics, and feedback mechanisms. Economic analysis methodologies are explored in Chapter 3 and opportunities for more advanced measurements of success, such as triple bottom line accounting, are presented.

Each of the chapters in this part focus on identifying and measuring those things that are of the most importance to the long-term sustainability of our natural and social infrastructure through the development and support of more highly evolved policies and programs.

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CHAPTER

The International Regulatory, Social, and Political Framework

1

Gary Hayward, Kathy Garvin

1.1 INTRODUCTION

When sustainable development is discussed, individuals both educated and uneducated in the topic delight in bantering about the notion that nobody knows what "sustainable development" *really* means. Well, for all of you who feel compelled to learn more, here's what it means:

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*
>
> The Brundtland Commission, 1987

Now is the time to answer a more pointed question: What does sustainable development really mean to me? To my project? To my organization? To my country? To my planet? It is true that sustainable development will have different implications at multiple scales for various populations, locations, governments, organizations, and projects. But there is no question about what sustainable development really means. We know what it means, and the time to incorporate it into our decision making across every single stitch making up the fabric of our existence is yesterday. Identifying and implementing sustainable practices is an involved, sometimes complex, but necessary process.

As the concept of sustainability moves to the forefront of our global culture, businesses and governments alike are striving to incorporate economic, environmental, and social considerations into their decision making. These efforts have resulted in a variety of forward leaps toward the ultimate goal of existing in a world where we can meet our present needs without compromising the needs of future generations. Depending on how developed a country is, sustainable land development can take form in a variety of ways.

For example, in the United States, efforts are being made to mitigate and prepare for climate change, specifically by controlling or preventing greenhouse gas emissions or by eliminating untreated industrial effluent discharges. However, in developing countries, more basic strategies are being explored and implemented to minimize soil erosion or to improve agricultural practices.

DOI: 10.1016/B978-1-85617-797-9.00001-0

Despite the varying implications that sustainable development has and will continue to have on all of the different elements currently existing on our planet, the framework in which sustainable development practices are identified and implemented remains the same:

Economic, environmental, and social impacts must be considered wholly for sustainable development to occur.

Without sustainable development, it is becoming a widely accepted fact that natural resources will be irreversibly depleted, leading to the planet's failure to sustain life. The path that leads us toward this calamitous destination involves polarized consumption of resources between the developed and undeveloped areas of the world as well as a blatant disregard for the resulting inequities associated with the quality of life between generations if sustainability fails to be considered in the context of land development.

As present generations stand witness to some of the already measurable consequences of unsustainable development, this portentous reality is gaining momentum as a compelling reason to promote and implement sustainable development practices.

Figure 1.1 illustrates a "ladder" for sustainable development as it applies to advanced industrial societies. This illustration has been adapted from *The Politics of Sustainable Development* (Baker et al., 1997) and serves as a diagram by which we can visualize holistic progression toward sustainable practices. But *how* do we distill these concepts into an action plan moving forward to implement sustainable practices? Read on.

1.2 GLOBAL INSTITUTIONS CURRENTLY SUPPORTING SUSTAINABLE DEVELOPMENT

As just described, the implications of sustainable development and its application in various parts of the world vary greatly. This is particularly the case in primarily rural developing countries where methods for sustainable development tend to focus on proper management of forest resources, agriculture in various forms, fishing, water resources, and/or energy. The underlying principle is that these forms of sustainable development help provide stability by (1) avoiding inherent boom/bust cycles, thus reducing poverty; (2) strengthening community development; and (3) promoting an overall healthier and more prosperous environment. As a result, many global institutions, along with most developing countries, are striving to better understand and define the linkages among poverty, economics, and people, and the importance of integrating sustainability considerations into informed decision making and policy guidelines.

1.2.1 The World Bank

The World Bank is not a bank in the common sense. It consists of two unique development institutions owned by 185 member countries: the International Bank for

Approach to Sustainable Development	Role of Economy and Nature of Growth	Geographical Focus	Nature	Policies and Sectoral Integration
"Ideal Model" of sustainable development	Right livelihood; meeting needs, not wants; changes in patterns and levels of production and consumption	Bioregionalism; extensive local self-sufficiency	Promoting and protecting biodiversity	Holistic intersectoral integration
Strong sustainable development	Environmentally regulated market; changes in patterns of production and consumption	Heightened local economic self-sufficiency, promoted in the context of global markets	Environmental management protection	Environmental policy integration across sectors
Weak sustainable development	Market-reliant environmental policy; changes in patterns of consumption	Initial moves to locate economic self-sufficiency; minor initiatives to alleviate the power of global markets	Replacing finite resources with capital: exploitation of renewable resources	Sector-driven approach
Treadmill	Exponential growth	Global markets and global economy	Resource exploitation	No change

Technology	Institutions	Policy Instruments and Tools	Redistribution	Civil Society	Philosophy
Labor-intensive appropriate technology	Decentralization of political, legal, social, and economic institutions	Full range of policy tools; sophisticated use of indicators extending to social dimensions	Intra- and intrageneration equity	Bottom-up community structures and control. New approach to valuing work	Ecocentric biocentric
Clean technology product lifecycle management; mixed labor- and capital-intensive technology	Some restructuring of institutions	Advanced use of sustain-ability indicators; wide range of policy tools	Strengthened redistribution policy	Open-ended dialogue and envisioning	
End-of-pipe technical solutions; mixed labor- and capital-intensive technology	Minimal amendments to institutions	Token use of environmen-tal limited range of market-led policy tools	Equity a marginal issue	Top-down initiative; limited state-environmental movements dialogue	
Capital-intensive production technologies; progressive automation	No change	Conventional accounting	Equity not an issue	Very limited dialogue between the state and environmental movements	Anthropocentric

FIGURE 1.1

The ladder of sustainable development in advanced industrial societies.

Reconstruction and Development (IBRD) and the International Development Association (IDA). Each plays a specific but collaborative role to advance the vision of an inclusive and sustainable globalization. The IBRD focuses on middle-income and creditworthy poor countries, while IDA focuses on the poorest countries in the world. Together they provide low-interest loans and interest-free credits and grants to developing countries for a wide array of purposes that include investments in education, health, public administration, infrastructure, financial and private sector development, agriculture, and environmental and natural resource management.

Because the World Bank provides vital financial and technical assistance to developing countries, it has established a set of environmental and social safeguard policies that funded projects must comply with. The objective of these policies is to identify and prevent and/or mitigate undue harm to people and their environment in the development process. They have often provided a platform for the participation of stakeholders in project design and implementation, and they have been an important instrument for building ownership among local populations.

Key among these safeguard policies is Operational Policy (OP)/Bank Procedure (BP) 4.01: Environmental Assessment. The purpose of OP/BP 4.01: Environmental Assessment is to improve decision making, to ensure that project alternatives under consideration are sound and sustainable, and to identify key stakeholders and ensure that potentially affected stakeholders have been properly consulted. This is considered to be the umbrella for the Bank's environmental and social "safeguard policies," which among others include Natural Habitats (OP 4.04), Forests (OP 4.36), Pest Management (OP 4.09), and Physical Cultural Resources (OP 4.11).

The primary objective of the World Bank's Natural Habitat safeguard policy (OP 4.04), for example, is to promote environmentally sustainable development by supporting the protection, conservation, maintenance, and rehabilitation of natural habitats and their functions. Its principle elements include

- Requiring a precautionary approach to natural resources management to ensure opportunities for environmentally sustainable development.
- Avoiding significant conversion or degradation of critical natural habitats, including those that are (a) legally protected, (b) officially proposed for protection, (c) identified by authoritative sources for their high conservation value, or (d) recognized as protected by traditional local communities.
- Giving preference to siting projects on lands that have already been converted or disturbed.
- Consulting key stakeholders, including local nongovernmental organizations and local communities, and involving them in design, implementation, monitoring, and evaluation of projects, including mitigation planning.
- Providing for the use of appropriate expertise for the design and implementation of mitigation and monitoring plans.
- Disclosing draft mitigation plans in a timely manner, in an accessible place, and in a form and language understandable to key stakeholders.

1.2.2 World Bank Affiliates

The International Finance Corporation (IFC), the Multilateral Investment Guarantee Agency (MIGA), and the International Centre for Settlement of Investment Disputes (ICSID) are affiliates of the World Bank, and collectively they form the World Bank Group.

The IFC provides investments and advisory services to build the private sector in developing countries, and its mission is to promote sustainable private sector development in developing countries, help reduce poverty, and improve people's lives. The IFC has taken a leading role in the promotion of socially and environmentally sound sustainable development. In 2006, it put into practice a policy on social and environmental sustainability that identifies a number of performance standards and includes a commitment by the IFC to review projects proposed for direct financings against them. These performance standards include

- Social and environmental assessment and management
- Labor and working conditions
- Pollution prevention and abatement
- Community health, safety, and security
- Land acquisition and involuntary resettlement
- Biodiversity conservation and sustainable natural resource management
- Indigenous peoples
- Cultural heritage

By applying these performance standards to the projects it finances, the IFC

- Enhances the predictability, transparency, and accountability of its actions and decision making.
- Manages social and environmental risks.
- Improves performance.
- Promotes both socially and environmentally sound sustainable development practices.

The MIGA provides investment guarantees for projects in a wide variety of *sectors*, covering all *regions* of the world. Its mission is to spur developmentally sustainable foreign direct investment to help create jobs, promote economic growth, and reduce poverty in its developing member countries. In October 2007, MIGA essentially adopted and began to implement the IFC's policy and performance safeguards on social and environmental sustainability (discussed earlier in the chapter) on projects for which it provides investment guarantees.

The ICSID, an autonomous international institution established under the Convention on the Settlement of Investment Disputes between States and Nationals of Other States (the ICSID, or the Washington Convention), has more than 140 member states. It is considered to be the leading international arbitration institution devoted to investor–State dispute settlement. In that the ICSID is not a direct or indirect source of finance lending, it has no reason to have social and environmental safeguard policies or environmentally sustainable development guidelines in place similar to those instituted by other members of the World Bank Group.

1.2.3 The Equator Principles

In October 2002, Algemene Bank Nederland (ABN) and Amsterdam-Rotterdam Bank (AMRO) and the IFC called on the major international project finance banks to assemble in London with the suggestion that guidelines for private financial institutions be drawn up. From this initiative, the Equator Principles were developed with leadership from ABN AMRO, Citigroup, Barclays, and West LB, and with strong support from the IFC. In June 2003, the Equator Principles were adopted by ten Western financial institutions. Since that time they have evolved to become the benchmark for private lending institutions around the world in managing social and environmental issues as part of their lending practices.

The Equator Principles represent a voluntary commitment and are based on the IFC's performance standards on social and environmental sustainability and on the World Bank Group's environmental, health, and safety general guidelines, which are applied globally and across all industry sectors by Equator Principles Financial Institution (EPFI) banks. As of April 2009, there are over 65 private lending institutions around the world that subscribe to the social and environmental sustainability commitments outlined in the Equator Principles. Further information regarding the specific details of the Equator Principles and subscribing EPFI banks can be found at *http://www.equator-principles.com*.

1.2.4 Sustainable Development Initiatives at the State Level

Historically, environmental degradation resulting from unsustainable development at the state level has either been disregarded or, once acknowledged, mitigated within a compliance-driven or "top-down" regulatory framework. Whether those governments attempting to mitigate environmental degradation will evolve into a more "bottom-up" or self-regulating framework remains to be seen. It is unlikely that countries will ever willingly decrease their gross domestic product (GDP) in an unprecedented act of goodwill. However, at some point, because of the planet's carrying capacity, the option to reduce production and consumption will no longer be a choice but an unavoidable result of limited or exhausted resources.

Meanwhile, sustainable principles are impacting regulatory trends throughout the world on a state level in an effort to mitigate the widespread and undeniably adverse impacts of irreversible environmental degradation and nonrenewable resource consumption. In the following sections, examples of state-level initiatives in both industrialized and transitioning nations that are significantly contributing to the promulgation of sustainable practices are summarized.

1.2.5 Member States

In the United States, the state level appears to be suitable for implementing sustainable development practices, as this is the governing level that is charged with provisions for much of the population's health care, education, and local resource management (i.e., pollution prevention). Ten states have governing bodies charged with assessing or enhancing sustainability on a statewide basis. The function of six of these bodies is limited to reducing the energy and environmental impacts of state government operations. Minnesota, New Jersey, Oregon, and Washington each claim to address sustainability from the combined environmental, social, and economic perspective intended by international bodies such as the Brundtland Commission (Engel and Miller, 2009).

Analysis of the three-legged stool that makes up sustainable development (environmental, social, and economic factors) shows that the U.S. regulatory framework is relatively advanced with regard to the market-driven framework for economic development and the compliance-driven framework for environmental regulation. However, little demonstrable progress has been made toward furthering high-quality federal education and health care programs in the name of sustainable development.

As mentioned previously, the U.S. top-down compliance-driven framework for environmentally regulating a generally burgeoning economy that is reliant on a society's propensity for unchecked and unbalanced consumption, though advanced in relation to other industrial societies, is unlikely to be the preferred model for implementing sustainable practices across the country.

1.2.6 The European Union

Within the European Union (EU), efforts are being made toward parallel objectives within member states. These include more stringent environmental targets, more comprehensive regulations to address sustainability, and an effort to standardize these regulations while moving away from consents and toward the ISO Environmental Management (EM) framework. These efforts have resulted in increased union consultations, increased reporting, more freely available data, and the establishments of benchmarks across the EU. The following three initiatives toward sustainable development were recently established.

The Renewed EU Sustainable Development Strategy, 2006

The renewed EU Sustainable Development Strategy (SDS) sets overall objectives and concrete actions for seven key priority challenges for the coming period until 2010, many of which are predominantly environmental:

- Climate change and clean energy
- Sustainable transport
- Sustainable consumption and production
- Conservation and management of natural resources
- Public health

- Social inclusion, demography, and migration
- Global poverty and sustainable development

The European Council's New Integrated Climate Change and Energy Policy, 2007

Given the central role of a sustainable energy policy in achieving climate objectives, and as a milestone on the way to a European energy policy, the European Council adopted a European Energy Action Plan with three goals: security of supply, efficiency, and environmental compatibility. Negotiations centered around agreement on a binding commitment to increase to 20 percent the proportion of renewable energies in overall energy consumption. This agreement is supplemented by the goal of introducing efficiency measures to cut by 20 percent the total energy consumption predicted for 2020.

In March 2007, the EU Council concluded the following:

> *Continued efforts need to be made to meet climate change and energy targets within the agreed deadlines. This will require continued attention to making a success of the Emissions Trading scheme; promoting renewables and sustainable use of biofuels and developing climate change adaptation strategies and plans.*

The Swiss Sustainable Development Strategy: Guidelines and Action Plan, 2008–2011

The Swiss Sustainable Development Strategy is derived from the axes of action identified as priorities in the Interdepartmental Sustainable Development Committee's status report:

- Combating global warming and managing natural hazards.
- Boosting economic productivity, in combination with a decoupling from resource and energy consumption.
- Using natural resources sustainably and reducing negative impacts on the environment.
- Ensuring fair access to social and economic resources and improving integration among all sections of the population.
- Increasing the effectiveness of the global fight against poverty and the promotion of peace.

From these stated priorities, 30 measures have been derived, breaking down into 8 key challenges and 3 additional challenges:

- Climate change and natural hazards
- Energy
- Spatial development and transport
- Economy, production, and consumption
- Use of natural resources
- Social cohesion, demography, and migration
- Public health, sport, and the promotion of physical exercise

- Global development and environment
- Fiscal policy
- Education, research, and innovation
- Culture

1.3 CONCLUSION

All over the world, scalable efforts are under way to move our societies toward a more sustainable existence. The EU, with its longstanding focus on sustainable development, will likely continue to serve as a forerunner in the development and institutionalization of sustainable policies. The United States stands to gain from this perspective in that, if it pays attention, it may benefit from some of the "lessons learned" from the European experience. For example, Americans have the opportunity to witness how European cap-and-trade policies have impacted various industries. In the EU, the power industry sector has gained much, while the manufacturing sectors have gained little. Although U.S. policies currently appear to be heading in the same direction, there remains the opportunity to restructure them with the hope of a system that would benefit all sectors—with the ultimate goals of energy efficiency and pollution prevention. Likewise, countries in transition may benefit from the U.S. experience of having thoroughly embraced the "top-down" philosophy of the 1960s, 1970s, and 1980s, only to evolve toward the more "bottom-up" approach seen in the 1990s that continues in the 21st century.

Technological advances are increasingly allowing societies all over the globe to operate more like a community of neighbors than they were able to in the past. Equally, these technological advances contribute to our sharing of the detrimental and often far-reaching impacts on our oceans and atmosphere, as well as our feedstock and agricultural lands. With this ever-increasing proximity, we are granted both the freedom to work together as neighbors and the opportunity to leverage one another's experience as we all strive toward the shared goal of living within a sustainable and balanced system. Chapter 2 discusses in greater detail sustainability initiatives currently under way in the public and private sectors.

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CHAPTER

2 Sustainability Programs: Policies, Metrics, and Feedback

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2.1 INTRODUCTION

Sustainability initiatives, whether undertaken by governments or private organizations, have three principle components: policy, metrics, and feedback. The first component of a sustainability initiative is to develop a policy of pursuing greater sustainability. Sustainability policies not only set goals, but often include creation of the institutional capacity to support, promote, and enforce sustainability. A large number of policy initiatives and specialized programs are already in place in both the public and the private sector.

For the results of sustainability initiatives to be verifiable, organizations and institutions must use metrics that assess aspects of sustainability. For some organizations, employing specific metrics may involve gathering new data or simply compiling and examining existing data from various sources. These metrics can be used to direct resources toward areas most in need of improvement or assistance, or to measure progress toward stated goals. There are many approaches to measuring sustainability, and a few of these are detailed in this chapter.

The programs most relevant to this book, however, are those that don't simply set goals and measure progress toward them, but move a step further by integrating sustainability metrics into decision making. A variety of frameworks are currently in development or in use that attempt to inject ecological feedback into decision-making models so that the effect of certain actions on natural resources and ecosystem services can be considered alongside more traditional concerns. These frameworks realign economic incentives, allowing organizations and individuals to see the true benefits of implementing sustainable practices.

2.2 POLICY

The first component of a sustainability initiative is to develop a policy that recognizes sustainability as a valid organizational goal and establishes criteria for

DOI: 10.1016/B978-1-85617-797-9.00002-2

measuring success. To be effective, many sustainability policies also must establish new institutional capacity that is capable of assembling and interpreting previously disparate data. In addition, often sustainability policies must establish new enforcement authorities.

2.2.1 Broad Policies

Policies calling for sustainability measures have been widely adopted by government agencies, state and local governments, and large corporations. They may include establishing specific goals such as reducing water or energy use, setting targets for alternative energy use, or making a commitment to purchase environmentally friendly products. Executive Order 13423, signed in January 2007, established a plan for promoting and enforcing sustainable development practices in the United States (Bush, 2007). This order sets objectives and guidelines for federal, state, and municipal agencies to reduce resource demands and increase efficiencies, including

- Improving energy efficiency and reducing greenhouse gas emissions of the agency, through reduction of energy intensity by 3 percent annually through the end of fiscal year 2015, or 30 percent by the end of fiscal year 2015, relative to the baseline of the agency's energy use in fiscal year 2003.
- Ensuring that at least half of the statutorily required renewable energy consumed by the agency in a fiscal year comes from new renewable sources, and to the extent feasible, the agency implements renewable energy generation projects on agency property for agency use.
- Reducing water consumption intensity, relative to the baseline of the agency's water consumption in fiscal year 2007, through life-cycle cost-effective measures by 2 percent annually through the end of fiscal year 2015 or 16 percent by the end of fiscal year 2015.
- Requiring agency acquisitions of goods and services to include the use of sustainable environmental practices, including acquisition of biobased, environmentally preferable, energy-efficient, water-efficient, and recycled-content products, and the use of paper of at least 30 percent post-consumer fiber content.
- Ensuring that the agency reduces the quantity of toxic and hazardous chemicals and materials acquired, used, or disposed of by the agency; increases diversion of solid waste as appropriate, and maintains cost-effective waste prevention and recycling programs in its facilities.
- Ensuring that new construction and major renovation of agency buildings comply with the Guiding Principles for Federal Leadership in High Performance and Sustainable Buildings set forth in the Federal Leadership in High Performance and Sustainable Buildings Memorandum of Understanding (2006), and that 15 percent of the existing federal capital asset building inventory as of the end of fiscal year 2015 incorporates the sustainable practices in the Guiding Principles.

- Ensuring that if the agency operates a fleet of at least 20 motor vehicles, the agency, relative to agency baselines for fiscal year 2005, reduces the fleet's total consumption of petroleum products by 2 percent annually through the end of fiscal year 2015, increases the total fuel consumption that is non-petroleum-based by 10 percent annually, and uses plug-in hybrid (PIH) vehicles when PIH vehicles are commercially available at a cost reasonably comparable, on the basis of life-cycle cost, to non-PIH vehicles.
- Ensuring that the agency, when acquiring an electronic product to meet its requirements, meets at least 95 percent of those requirements with an Electronic Product Environmental Assessment Tool (EPEAT)–registered electronic product, unless there is no EPEAT standard for such product, enables the Energy Star feature on agency computers and monitors, establishes and implements policies to extend the useful life of agency electronic equipment, and uses environmentally sound practices with respect to disposition of agency electronic equipment that has reached the end of its useful life.

Some of the goals just listed are quantifiable, such as reducing energy intensity by 30 percent, increasing the use of alternative fuel by 10 percent annually, and reducing water use intensity by 2 percent annually. Many federal agencies and state governments have adopted their own sustainability goals that mirror the federal government's or are more stringent.

This form of broad policy approach to sustainability issues is not new in the United States. Since 1970, the National Environmental Protection Act (NEPA) has required all federal agencies to assess the environmental impact of proposed actions and to ensure that the interested and affected public is informed by environmental analyses. Under NEPA, any action the federal government proposes requires a comprehensive environmental planning assessment to determine whether or not it will significantly affect the human environment.

Based on the conclusions of the NEPA assessment and public feedback, the government then decides whether or not to proceed with the proposed action. The purpose of the assessment is to ensure that the human environment is not significantly adversely affected as a result of the government's action. The significance of impacts is measured by qualified professional NEPA practitioners.

Components of the human environment considered under each of the assessments typically include water resources, water quality, geology, wildlife, threatened and endangered species, essential fish habitat, aquatic and terrestrial ecology, and air quality, as well as socioeconomic resources such as employment, population, environmental justice, and land use, and other components such as noise, transportation, cultural resources, and aesthetics.

Local and state governments may pursue sustainability by mandating specific environmentally friendly technologies as a matter of public policy. A variety of organizations, such as the U.S. Green Building Council, have created sustainability standards that can be voluntarily adopted or used to develop building codes and city ordinances. Minnesota Planning, a state agency, developed an extensive collection of model ordinances that can be used by local governments to encourage sustainable development (Minnesota Planning EQB, 2000).

2.2.2 Institutional Capacity

Closely related to the broad policy initiatives just presented is the creation of the institutional capacity to oversee, promote, and enforce sustainability initiatives. For many organizations, several existing, separate programs can be pulled together within a concerted sustainability initiative. The Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), created by a reorganization of separate programs within the DOE in 2002, is tasked with overseeing the federal government's compliance with Executive Order 13423. It also has responsibility for a variety of programs that support efficiency within the private sector. It funds the development of a large range of renewable energy resources, and has more than 500 ongoing research projects that aim to improve efficiency within "energy-intensive" industries, such as steel, petroleum, and mining.

The U.S. Environmental Protection Agency (EPA), although it is responsible for protecting the environment, does not have a structure conducive to encouraging sustainability. With separate offices for air, water, toxics, and waste, as well as distinct regional offices, the EPA's structure can encourage insular rules and regulations that do not consider the full effects of policies or actions. In addition, the programs that did exist to encourage sustainability were disjointed: An inventory in 2003 identified more than 100 "smart growth" initiatives in five separate offices and in the regions.

In 2004, the EPA developed a Smart Growth Strategy that tried to make the agency's approach more consistent. The strategy calls for the agency to engage in educational efforts with state and local governments and the public to discourage "barrier regulations" such as local rules discouraging mixed-use development. It also calls on EPA officials to ensure that EPA regulations regarding water infrastructure, stormwater, and air quality do not have the unintended consequences of discouraging innovative, sustainable practices (EPA, 2004).

Reuse is a key to sustainable development, and dedicated programs are often necessary to enable and encourage it. The EPA has developed a Brownfield Redevelopment Program that can inform, support, and fund the redevelopment of contaminated properties. This program has significantly contributed to the redevelopment and reuse of formerly contaminated lands designated as unusable. Brownfields are real property, the expansion, redevelopment, or reuse of which may be complicated by the real or potential presence of a hazardous substance, pollutant, or contaminant. Cleaning up and reinvesting in these properties take development pressures off of undeveloped, open land and both improve and protect the environment.

2.2.3 Regulatory Authority

In some cases, the most important aspect of creating a sustainability initiative is to establish regulatory authority in new or existing agencies. In South Carolina, attempts by the state's environmental agency to create a water plan that protects minimum flows within rivers have been stymied by the fact that state law does not allow the agency to require permits for water withdrawals. In neighboring Georgia in 2008, the state environmental agency passed a water plan to regulate the consumptive use of water to protect downstream flows and water quality through a newly created system of regional water boards. However, the agency has not yet been given the authority to enforce regional rules through its water permitting process.

These problems are not uncommon. Historical legal doctrine has favored the property rights of upstream water users and can stand in the way of attempts to require minimum stream flows and limit withdrawal amounts. And these are not the only legal and regulatory precedents that can hamper sustainability initiatives. As stated earlier, some common stormwater, zoning, and planning ordinances can actually obstruct sustainable development. Many times, a key part of sustainability policy is first dismantling these obstacles.

Another problem exemplified by state water planning is jurisdictional hurdles. Watersheds—like other ecosystems and natural resources—cross over many political boundaries, making it difficult for a local, state, or even national government to protect resources over which it has only partial control. The necessity for bodies that can act as custodians of large, trans-jurisdictional ecosystems has been long recognized. The U.S. Army Corps of Engineers was given regulatory authority over U.S. water resources in 1824, though they did not take an active role in managing these resources until 1950, and still leave most water planning and protection to state governments. Recently, states began changing their legal and regulatory structures to allow for a watershed approach to water management (Feldman, 2007).

2.3 MEASUREMENT AND REPORTING

To make real and recognizable progress toward goals of sustainability, organizations must have a means for measuring the sustainability of their actions and decisions. In some cases, efforts must be made to gather new data; in others, existing data can be analyzed or presented in new ways so it can gauge sustainability and identify areas most in need of additional attention. There have been many efforts in both the private and public sector to develop frameworks for gathering and compiling data.

2.3.1 Global Reporting Initiative

For decades, corporations have been aware of the need to protect their reputations and portray themselves as socially and environmentally responsible. The responsibility of a company, however, especially a sprawling multinational with operations around the globe, can be hard to measure and quantify.

In the early 1990s, Boston-based CERES, a nonprofit comprising public interest groups, environmental organizations, and investors, saw the need to develop a standardized way for companies to demonstrate their compliance with sound social and environmental practices. It developed the Global Reporting Guidelines, a standardized framework for gathering and presenting data about companies' sustainability. The guidelines include dozens of performance indicators that companies can use to gauge and communicate their corporate social responsibility. Indicator categories include human rights, labor practices, product responsibility and environmental performance.

Basic environmental indicators include water withdrawals, energy consumption, amount of emissions and effluent, and the effect of the organization's operations on biodiversity and sensitive habitat. Indicators in other areas include rates of injury, percentage of employees covered by collective bargaining agreements, and the organization's position on public policy initiatives. Each indicator includes protocols for gathering relevant data and presenting it in a sustainability report. Reports must include future targets for each indicator as well as data for the previous two years to illustrate the organization's trend on that indicator (GRI, 2006).

Not all indicators are appropriate for all organizations. The Global Reporting Initiative (GRI) framework allows individual organizations to select indicators that are most applicable to them. There are several levels of compliance; however, certain "core" indicators must be included by any organization for its report to be considered in minimum compliance with GRI guidelines. An organization with a nascent sustainability reporting program can begin with the basic core and add reporting on additional indicators over time to bring itself into higher levels of GRI compliance.

GRI guidelines were first published in 2000; in the first year, 50 organizations released reports that adhered to them. Now, according to the 2008 KPMG International Survey of Corporate Responsibility, systematic reporting on sustainability has become the norm among large companies (KPMG, 2008). That survey found that 80 percent of the 250 largest companies worldwide were releasing sustainability reports, most of which followed, at varying levels, the GRI guidelines. Nearly 1000 organizations have registered their reports with the GRI.

There is increasing pressure for companies to record and present sustainability information to stakeholders and the public. In 2003, the European Union passed a directive requiring companies to include social and environmental impact information in their annual reports. The directive states that annual reports should include "non-financial key performance indicators relevant to the particular business, including information relating to environmental and employee matters" (European Parliament, 2003).

Twenty-one EU member states have now implemented these requirements in their national legislation. However, many EU companies may be missing the spirit of the 2003 Modernisation law (FEA, 2008). Large differences in content and the irrelevance of nonfinancial information in annual reports suggest that standards regarding what to report to provide a fair review of development and performance are not yet fully developed.

Through the GRI, reporting can be an effective way for companies to judge the sustainability of their practices and to provide investors and consumers with quantifiable information about an organization's adherence to sustainable and socially responsible principles. Few companies are fully integrating considerations of sustainability into their balance sheets. Even when sustainability sections are included in required annual filings, sustainability reporting is still segregated from traditional financial data. One example of a fully functional, monetized triple-bottom-line accounting system is provided in Chapter 25.

2.3.2 U.S. Department of Agriculture's Ecosystem Sustainability Framework

The indicator approach, because of its flexibility, can be effective for a wide variety of organizations. The U.S. Department of Agriculture's (USDA's) Natural Resource Conservation Service (NRCS) used an approach similar to the GRI's and developed a series of indicators to evaluate the sustainability of agricultural systems—defined as the ability of a system to meet the needs of the farmer while conserving natural resources (NRSC, 1999). One goal of the project was to find a way to take the large amount of data that was already being gathered and use it to create a measure of sustainability. The NRCS selected 18 indicators that could be measured using readily available data from the Agricultural Census, the Natural Resources Inventory, and the Conservation Tillage Information Center's Tillage Survey. Indicators were applied on a county-wide basis.

In their initial study, the NRCS used both economic indicators, such as the yield of significant crops, change in land values, and the net cash return for farms, and environmental indicators, including erosion, percentage of tree cover, and use of conservation tillage. At the time the original framework was developed, the NRCS intended to develop new indicators using soil and climate data. This framework can be used to direct resources to areas in most need of assistance.

2.3.3 The Millennium Ecosystem Assessment and Ecosystem Services Valuation

One way to measure sustainability is to assess the value of the services provided by ecosystems, either natural, such as forests, or highly developed, such as urban or agricultural areas. Ecosystem services, as defined by the UN-sponsored Millennium Ecosystem Assessment (MEA), include

- *Provisioning* services—supplying food, water, fiber, or timber
- *Regulating* services—those processes that mitigate disease, water quality, climate, and catastrophic events such as floods or fires
- *Cultural* services—opportunities for spiritual or aesthetic appreciation and recreational use
- *Supporting* services—soil formation photosynthesis and nutrient cycling.

The MEA was initiated in 2001 and modeled on the structure of other international scientific initiatives such as the International Panel on Climate Change and the Global International Waters Assessment. Utilizing data that was already available, the MEA endeavored to measure the value of ecosystem services by assessing the effect on people of changes in those services, such as changes that occur when water is impounded behind a dam or when forest cover is depleted. It evaluated the economic and public health costs associated with circumstances arising from degradation of ecosystem services. These included algal blooms, increases in flooding, loss of tourism revenue, and polluted water supplies.

The idea behind the MEA's approach is that, since ecosystem services are not traded in traditional markets, markets fail to allocate natural resources properly. These vital services are not always put to their most beneficial and effective use because a great deal of their value is "nonmarket." For example, the MEA found that the true value of a forest for hunting, recreation, and carbon sequestration far outweighs the economic value of the timber it can produce. But since the prior variables are normally not measured, it can be hard for decision makers to understand the forest's best use. The true costs and benefits that result from varying uses of natural resources are hidden.

The 2005 MEA report is concerned primarily with measuring ecosystem services and noting where their loss has had a negative impact on human well-being. However, the report does make recommendations as to how feedback mechanisms can be created so that these measurements are incorporated into the economic structure, allowing the market to play a role in allocating natural resources. These recommendations, which include taxes and fees tied to environmental impact, offset programs, and cap-and-trade markets, will be discussed in the next section, as well as tools developed by other organizations using an ecosystem services approach. For further discussion on ecosystem services and their valuation, see Chapter 25.

2.4 FEEDBACK MECHANISMS

Many programs have found ways to integrate sustainability metrics into decision making so that the effect of certain actions on natural resources and ecosystem services can be considered alongside more traditional concerns. These frameworks realign economic incentives, allowing organizations and individuals to see the true benefits of implementing sustainable practices.

2.4.1 Taxes and Fees—French River Basin Agencies

One of the economic tools recommended by the MEA to support sustainable policies is for countries to implement taxes and fees tied to environmental damage. France, with its system of River Basin Agencies, was one of the first countries in the world to attempt to put a price on environmental damage and make those who do the damage pay the cost (Feldman, 2007). The six River Basin Agencies, which were established in 1964, levy fees against those who use and discharge into water.

The fees are devised using a complex formula that takes into account the mass of pollutants discharged as well as other variables that measure the economic impact of a discharger, such as the cost to treat the specific pollutants and the amount of time it takes pollutants to decompose. The agencies sustain all water-related programs with these fees, including water treatment and supply and pollution abatement. They also use the money to provide additional economic incentives by subsidizing water-efficient technologies and other improvements in water use.

France's program has been incredibly successful in reducing water pollution. Organic waste discharges have declined by an average of 4.4 percent a year since 1980. In addition, 50 percent of toxic waste has been eliminated. The program is not perfect. It focuses on the costs related to human consumption concerns and does not account for damage to ecosystems. Still, it is well established and effective in folding at least some of the costs of pollution into the industrial bottom line.

Other countries have attempted to implement tax and fee systems. Brazil, for example, requires developers to compensate for their environmental impacts by making payments to the National Protected Areas System (Bezerra, 2007).

2.4.2 Cap and Trade—The Acid Rain Program

Governments may also create markets through "cap-and-trade" programs, in which a facility is allowed a set level of emissions but can trade the difference between its actual emissions and the permitted amount to other facilities that are emitting more. These programs harness the power of the market to provide incentives for efficiency, and they allow facilities to profit from employing innovative technologies that may not have otherwise been cost-effective. Cap-and-trade programs also allow pollution control to occur where it is the most effective and least expensive, rather than imposing one-size-fits-all limits on all facilities regardless of their ability to achieve reductions.

Cap-and-trade schemes have been successful. The Acid Rain Program in the United States, which focuses on reducing sulfur dioxide and nitrogen oxide emissions, was first created in 1990. It has reduced sulfur dioxide emissions by 43 percent, which is beyond the program's long-term goal. Emissions of nitrogen oxides are less than half of what they were projected to be without the program. As a result, there have been substantial decreases in nitrogen and sulfur deposition (EPA, 2007).

Although cap-and-trade programs are most often discussed in relation to air quality, they can be implemented for a variety of permitted discharges. The EPA has encouraged states to implement water quality trading as a way to control nutrients, sediments, and pollutants (EPA, 2003). Water pollution trading systems may allow trading not only between industrial facilities, which are known as pollution "point sources," but between point sources and agricultural and forestry areas, which are considered "nonpoint sources" of nutrients, sediment, and agricultural chemicals to surface waters. In southern Minnesota, the Southern Minnesota Beet Sugar Cooperative (SMBSC) was able to expand its operations without violating limitations on phosphorous discharges into the Minnesota River by working with area beet growers to adopt erosion control best management practices (BMPs). Water quality was protected without limiting the ability of the SMBSC to grow (Fang et al., 2007).

2.4.3 Offsets and Mitigation Banking

Another economic instrument that is recommended by the MEA and has had success in some areas is the sale of offsets. Offsets seek to balance environmental harm in one area with environmental gains in another. Wetland offsets have been used in the United States since the 1970s. When losses of wetlands are unavoidable during a development project, the project owner can attempt to create or restore wetlands elsewhere on the site. If that is not possible, wetland "credits" can be purchased from a third-party wetland bank.

Essentially, entrepreneurs can build large-scale mitigation projects and then profit from them by selling the credits created to developers. This system encourages large mitigation areas that can support higher-quality wetlands than project-by-project mitigation. It also allows mitigation projects to be located in ecologically optimum areas (Bezerra, 2007).

The concept of wetland mitigation banking has now been adapted to the preservation of endangered species. When a project threatens the habitat of a protected species, its developers may purchase conservation credits. Conservation banks can be created by establishing conservation easements for existing habitats, restoring damaged habitat, or creating new habitat with specified biological characteristics.

Offset programs can be designed in a variety of ways to protect a range of natural values. Several Australian states have offset programs to protect native vegetation. Brazil, Costa Rica, and the European Union recently adopted biodiversity offset programs. Both Canada and New Zealand implemented forms of offset programs to protect their fisheries (Bezerra, 2007).

2.4.4 U.S. EPA's Ecological Research Program

The EPA's Ecological Research Program is using the ecosystem services valuation approach to develop tools that enable decision makers to consider the values associated with different land use and planning decisions. The program selected four areas undergoing significant changes in land use. Three are experiencing rapid population growth; in the fourth, additional land is being put to agricultural use to satisfy biofuel demands (EPA, 2007).

One of the areas experiencing a population boom is Tampa Bay, Florida. The Tampa Bay estuary is one of the most productive natural systems in the world, and a significant amount of the economic activity in the area is dependent on its health. The EPA is partnering with local stakeholders to determine the value of Tampa Bay's ecosystem services in terms of human well-being. Researchers are developing models that simulate the long-term impact of development decisions on these services. Using such tools, planners can account for the value of the ecosystem services that may be lost according to different development scenarios, and make informed decisions regarding the sustainability of land use plans.

The Midwest study area covers 13 "breadbasket" states. Because of increasing demands for biofuels, land that is currently enrolled in conservation programs is being converted to cropland. Increases in cultivation can stress soil and water quality. The goal of the Ecological Research Program in this study area is to create incentives that will “pay” for the social benefits accruing from ecosystem services. These incentives could encourage optimal agronomic practices, protect wildlife habitat and water quality, and preserve the ecosystem’s ability to control floods and store carbon (EPA, 2008).

Researchers in the Ecological Research Program are looking for ways to integrate these natural values into I-FARM, a popular online tool that farmers can use to analyze the profitability of different crops. They are also trying to integrate these values into Purdue University’s Long-Term Hydrologic Assessment/Environmental Quality Incentives Program, which offers decision support on water BMPs.

2.4.5 U.S. Department of Defense’s Natural Infrastructure Valuation

The Department of Defense (DoD) has an extensive voluntary framework for incorporating the value of natural resources and ecosystem services into decision making. Its Natural Infrastructure Valuation is an example not only of how sustainability considerations can be integrated into decisions but also of the important role that other economic tools already discussed can play in this kind of comprehensive framework.

The DoD has published extensive guidance on methods for estimating the value of natural assets and the services they provide. The assets most commonly evaluated in practice are tradable allowances (such as air emissions or carbon credits, tradable water quality or discharge credits, or wetland and conservation mitigation credits), water rights, timber production, crop production, mineral resources, recreational opportunities, aesthetic assets, and stream assets. As this list makes evident, the DoD framework relies substantially on market mechanisms devised to promote sustainability.

This framework can help military installations realize opportunities for creating value, such as by restoring wetlands on base so wetland mitigation credits can be sold or by recognizing the values inherent in permit “headroom.” Installations can also use the framework to determine if they are charging reasonable rates for their timber and mineral rights leases. They are encouraged to focus on off-base natural resources when possible, such as restoring wildlife habitat or reducing total emissions in surrounding areas to relieve regulatory pressures on the bases themselves.

2.5 CONCLUSION

A wide variety of organizations and governments have adopted sustainability programs. The most effective are those that go beyond vague mission statements and aim for quantifiable results. A wide range of options is available that can help realign economic accounting and incentives so that sustainability initiatives are not an encumbrance but are instead a way to recalculate costs to better represent real values.

Sustainability initiatives can reduce expense by building a stronger connection between certain activities and the costs they incur, thereby establishing disincentives for inefficient behavior. The best and most successful sustainability schemes are those that are flexible enough to allow for innovation and can be tailored to a variety of needs and abilities.

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CHAPTER

Ecological Economics

3

Sam Collier

A theoretical physicist is about to make a presentation to a roomful of engineers. Just as he puts his first sheet of calculations onto the overhead projector, the power goes out in the entire building. Out of the darkness, an engineer in the back of the room sneers, "Assume electricity!"

3.1 THREE CAPITALS

The trajectory of human economic and technological development has assumed certain fundamentals that, in fact, cannot be taken for granted. What we typically think of as "the economy" places an emphasis on one type of capital: financial capital. The metrics we use to describe the economy's health, the currency we trade to reflect value within it, and even the terms we use to promote or limit certain activity ("that makes economic sense" or "that might be a good thing to do, but it doesn't make economic sense") are essentially rooted in an assumption that financial capital is what the economy is all about.

But because all this financial activity takes place between humans, there is a capital that is assumed but poorly measured: the "stocks" of human capability, productivity, and well-being, and the flows of human creative and productive effort we now refer to as social capital.

And because these transactions among humans all occur within our life support system (and are wholly dependent on that system continuing to be healthy), there is another capital that is assumed but poorly measured: the stocks and flows of clean air, clean and abundant water, wildlife habitat, and a stable climate system. We now refer to these as natural capital.

Social capital is just as important to the economy as the financial capital that reimburses it for its efforts. Natural capital is just as important, if not more so, because if it fails, the other two cannot exist. Financial and social capital exist only within the natural world and require a healthy natural world in order to flourish.

DOI: 10.1016/B978-1-85617-797-9.00003-4

The financial downturn of 2008 upended long-held assumptions about financial capital. One assumption was that housing prices always increase. That was certainly the case for as long as most people (younger than 80) can remember. Many homeowners borrowed money they could barely afford on the assumption that their house would always increase in value. Thus, even if they could barely afford their fixed-rate mortgage at the beginning, over time, they believed, their income would rise while their mortgage would not and they would have room in their budget for other things. That same assumption rendered adjustable-rate mortgages extremely vulnerable. When payments rose on these mortgages, they were among the first to trigger defaults and foreclosures, and real estate prices began falling for most houses. Once housing prices started to fall, the assumption of increasing house values, which underlay billions of dollars in loans, crumbled, and the downturn began. The fact that financial wizards had leveraged these loans many times over multiplied the impact of the defaults, setting off a global financial crisis.

It is easy to see, looking back, that inaccurate and inadequate information flows kept people from recognizing the devastation on the horizon. Because so many loans were bundled, "securitized," and sold around the world, investors could not peer into the assets within the bundles to see if their underlying value was sound. We had up-to-the-minute information on Dow Jones Industrial Average trading, and could tell the prices of stocks of banks, mortgage companies, and securities companies at every moment of every day. Nevertheless, we had no measure of the soundness of the homes undergirding so much of the mortgage lending business or of the soundness of the budgets of the homeowners who owed on the mortgages. It was like looking at the speedometer with little regard for the oil pressure or gas gauges, when what was most needed was a look at the map.

We will eventually recover from this debacle, with a monetary cost and level of pain that we cannot yet predict. We will learn lessons and likely apply them to our financial capital system so that we prevent another debacle of this nature. Because these systems are of, by, and for humans, we have much greater control over how they respond to certain human drivers. Injection of capital by central banks may free up cash to invest, stimulate new economic activity, and get the financial system humming again.

But what lessons can we apply to our social capital system or our natural capital system? In these systems, the stakes are much higher, particularly with regard to natural capital. Because of its scale over space (often the entire globe) and time (in some cases hundreds of thousands of years or more), the natural capital system is vulnerable to irreversible damage on a global scale. There is no reset button on the planet.

It is often said that what gets measured gets done. But the opposite is also true: What does not get measured may not get done. So what are we *not* measuring what *must* get done? Humans have a tremendous stake in the value of the ice sitting on top of Greenland. It is far more important to New York City than the combined value of all the buildings in Manhattan. This sounds like a preposterous claim, but consider: If Greenland's ice slides into the ocean, Manhattan will be inundated with water. If all of Manhattan is inundated, the first floor (at least) of most buildings will be unusable. Thus the importance of the ice staying on top of Greenland is immense.

But none of our national economic measures include the value of keeping this ice on top of Greenland, so we have no way to factor into our economy the threat it faces from climate change. And because the ice is so massive (scale over space) and hundreds of thousands of years in the making (scale over time), all the king's horses and all the king's men will not be able to put it back together again. Once it is gone, Greenland's ice is gone for millennia.

We *have* been rather rapidly awakening to the stake we humans have in bees. The natural capital of pollinators such as bees is, like land-based ice, so fundamental as to be taken for granted. Only as we lose a fundamental function, such as pollination, do we see the value it has been providing all along. We can even make crude measurements of a fundamental function's value as we try to restore or replace it, or learn to do without it. But the better approach is to acknowledge these values up front, measure them, and then manage against these metrics to protect these critical values.

3.2 AN ECOLOGICAL ECONOMICS APPROACH

Ecological economics acknowledges the three capitals—social, financial, and natural—that are fundamental to our well-being. It is a discipline that takes lessons from ecology about how nature cycles nutrients, how these cycles create interdependent systems, and how these systems interact with each other to form larger, more complex systems. It then applies these ecological lessons to economics.

3.2.1 Develop a Vision of Prosperity

Ecological economics integrates an ecological component into the traditional financial approach to economics that has ignored natural and social concepts, or at best dealt with them only as subsets of the financial picture. It acknowledges that humans act in order to survive and even to prosper. In order to organize our activities to prosper, we need a shared vision of prosperity. We must get back to fundamentals to remind ourselves of what we really want and not just what we will settle for (Figure 3.1).

3.2.2 Measure What Matters: Accurate Measures

Only when we establish a vision of what we *really* want can we establish accurate measures of whether we are doing the right things to get it. When we establish a vision of health, we can begin to measure whether we are healthy rather than measure our health in medical expenditures. Low expenditures may be an indicator of good health or of a poor health delivery system; high expenditures may indicate poor prevention and high remediation. Neither is a good measure of our health.

REALLY WANT	WILL SETTLE FOR
Self-esteem	Fancy Car
Mobility	Lots of Roads
Health	Medicine
Human Happiness	Gross Domestic Product
Permanent Prosperity	Unsustainable Growth

FIGURE 3.1

What we want versus what we'll settle for.

The gross domestic product (GDP) calculation is a poor measure of our economic well-being. The GDP is blind to future problems because it does not take resource depletion into account until *after* the damage is done. Because it measures only cash transactions, with no regard to whether the transaction is a positive one—or even sustainable over the long term—the GDP sends very confusing and inaccurate signals about true prosperity, well-being, and sustainability.

The GDP calculator does not have a subtract button; it cannot distinguish positive cash transactions from risky ones. A high divorce rate actually is better for the GDP than a low one, since lawyers, judges, realtors, and many others are involved in divorce, and cash changes hands often (Cobb, Halstead, and Rowe, 1995). Likewise, a pandemic spins the GDP meter faster, as vaccines, hospitalizations, doctor visits, and other remediation indicate much cash changing hands. However, we are not more prosperous for suffering through a pandemic.

Better Measures Are Being Developed

Calculating an alternative measure of prosperity, such as a genuine progress indicator (GPI), a sustainable gross domestic product (SGDP), or an index of sustainable economic welfare (ISEW), is an important early step toward sustainability because it gives a more accurate measure of prosperity. By reforming the measure with things we value, we can gauge how we are doing in meeting our real goals and desires (Redefining Progress, 2009).

China began trying to account for natural capital in its gross domestic product calculation, developing a "Green GDP" measure in 2004 when the Chinese National Bureau of Statistics and the State Environmental Protection Administration began to factor environmental degradation and resource depletion into China's GDP. However, when the report was released in 2006, it was widely criticized. It stated that environmental pollution cost China the equivalent of U.S. $64 billion in 2004, representing 3 percent of Chinese GDP. The Chinese government admitted that groundwater and soil contamination were not included in the accounting. Even among the evaluated topics, there were missing items and underestimates—a fact painfully obvious to many Chinese struggling with unhealthy air and water (Economy, 2006).

Despite the admitted limitations of the Chinese green GDP valuations, to those advocating rapid development, even these figures of damage were too controversial. The project's main proponent, Vice Minister Pan Yue, admitted there are big challenges: "How do you decide the value of natural assets when they are not traded in the market and thus have no price? How much is the cost of felling a part of a forest? We don't know because we don't know how to count the ensuing animal extinction and soil erosion" (Economy, 2006).

Bhutan has undertaken a very positive national metric—one measuring happiness. The term "Gross National Happiness (GNH)" coined by the King of Bhutan, His Majesty Jigme Singye Wangchuck, defines development not in terms of an economic measurement but in terms of the people's happiness. According to Bhutan's minister, Dasho Meghraj Gurung, "The ideology of GNH connects Bhutan's development goals with the pursuit of happiness. This means that the ideology reflects Bhutan's vision on the purpose of human life, a vision that puts the individual's self-cultivation at the center of the nation's developmental goals, a primary priority for Bhutanese society as a whole as well as for the individual concerned" (Center for Bhutan Studies, 2004). Like the other alternative measures of prosperity, the GNH is a work in progress. Still, the practice of devising alternative measures is a powerful start to a dialogue on what matters to our society and how to reflect this in public as well as private life.

More versus Plenty: When Is Enough Enough?

Roberto Goizueta, the late CEO of Coca-Cola, explaining in April 1997 that one billion Cokes are sold every two days, stated:

> *Not long ago, we came up with an interesting set of facts: A billion hours ago, human life appeared on Earth. A billion minutes ago, Christianity emerged. A billion seconds ago, the Beatles changed music forever. A billion Coca-Colas ago was yesterday morning.*
>
> *The question we ask ourselves now is: What must we do to make a billion Coca-Colas ago be this morning? By asking that question, we discipline ourselves to the long-term view.*

The chilling thing about this statement is not that there may be a great deal of environmental destruction (not to mention tooth decay and obesity) if Mr. Goizueta's goal of "a billion Cokes ago … this morning" is achieved. In fact, the Coca-Cola Company could actually find a way to deliver this many beverages in a sustainable manner. No, what is truly chilling is that even if the company reached this goal, it would not be enough. The system is designed to deliver more, more, more in a world that operates cyclically. Somewhere in the system, stagnation or collapse (of something) is inevitable.

Goizueta's remark is a very apt description of the system as it exists now, but it is not a long-term view. Rather, it is a relatively naïve growth *benchmark* that, if reached, will be replaced with another growth benchmark (e.g., a billion Cokes ago in the last hour). Growth—not nutrition, well-being, flavor, or even refreshment—is the end goal of this system. There will never be enough, never a steady state. Perpetual growth is what makes cancer cells so dangerous to an organism—the cells grow until death results.

The challenge, then, is to find two types of measures of prosperity. The first is a measure of *plenty* or *enough* of those things that cannot be delivered in endless supply. In the United States, we measure housing starts as an indicator of economic vitality. But is there anyone who can say that the ultimate goal is to have houses entirely covering the landscape? Even leaving aside the question of nature, where would people work and shop in a nation covered in houses? And how would we continue to have housing starts as a measure of economic growth if there was no place left to build? So, if implicit in the housing starts metric is the understanding that there is a number that represents *enough* houses, or *plenty* of housing, how do we incorporate this into our measures of economic vitality?

One way would be to merge in a quality (as opposed to quantity) metric, such as the percent of adequate housing, to measure how nice the houses are. This allows for improvements in houses to count as economic progress, so that house improvements show up alongside housing starts, and we don't have to move in order to increase the housing metric. An even better way would be to incorporate social capital into the housing metric. Measuring the percent of the population in adequate housing would also measure whether we all have a home. Under the current metric, it is entirely possible—and in fact it has been the case in the United States—that housing starts can be booming in a time of rampant homelessness. This indicates how poor the housing starts metric is. It says nothing about the quality of the house or the affordability of housing for everyone. We can succeed in meeting a faulty metric and be poorer as a society in the process.

One way to incorporate natural capital would be a metric that compares the percentage of the population in adequate housing to the percentage of the landscape fully functioning in its natural state. If low-impact housing is built, this ratio improves even while more homes are being constructed, because more of the developed environment is compatible with nature. All manner of green building techniques (e.g., green roofs, pervious paving, backyard habitats) would improve the metric and more accurately reflect all three capitals.

The second type of measure of prosperity would find things that in fact can be delivered sustainably in endless supply. However, the critical requirement is to find those things that truly can be endlessly supplied, without hidden costs or unintended consequences.

3.2.3 Accurate Pricing: True Cost Accounting

Currently, the true cost of a good or service is not represented on the price tag, but includes a range of external costs—public subsidy, tax breaks, impacts on third parties, impacts on future productivity of the land, air and water, and so forth (CTA, 1998). As long as these costs are not included in the price, the information is inadequate and signals to the market are distorted. Someone outside the decision chain is paying the externalized costs and paying them out of proportion to his or her use of the good or service. When those who pay have no say in whether a certain activity occurs, they have little means to exert pressure to rectify the cost, and the market does not get a chance to respond.

Externalized costs most hurt industry innovators (leaders) while rewarding industry laggards with lower operating costs. The incentive for businesses to be responsible and lead by resolving unintended consequences is reduced because if you do nothing, you get a bigger subsidy from someone else (including future generations). To lead is to leave that subsidy sitting on the table, which executives with a fiduciary duty to shareholders have a hard time explaining. Certain businesses that are leading the way in sustainability are doing a brilliant job of marketing this leadership as a positive, but they do so while pushing uphill against skewed market signals.

In the absence of accurate prices, wise managers can employ planning tools to prepare for the eventual day when the bill comes due on externalized costs. The idea of “shadow pricing” helps in long-term planning and budgeting. Shadow pricing on future energy infrastructure (or energy-consuming infrastructure such as buildings, neighborhoods, vehicles, and other machines) includes a “cost adder” to reflect externalities such as greenhouse gases, fuel depletion, and other issues that will affect the price in the future. Putting infrastructure in place with a 30-year life span should be done using a “greenhouse gas adder” that rises from the present zero dollars per ton of CO_2 to figures of $20 to $300 per ton for carbon costs (Tyran, 2007). Projections should also consider rapidly escalating fossil fuel prices based on the type of fuel proposed and the foreseeable price rise in that fuel over time.

Failing to factor in carbon costs and sharply rising fossil fuel costs is risky for medium- to long-term investments, and it is bound to bring surprises in a matter of a few years. On the other hand, factoring in these costs opens up new possibilities for investing in strategies that reduce them.

3.2.4 Methods of Valuing Ecosystem Services

As organizations and governments begin to account for the value of services that an ecosystem provides, they will encounter a fundamental challenge: What currency should measure and compare services? Because financial capital is measured in monetary units, using a financial currency to measure the value of natural services has great appeal. A monetary value placed on the loss of a forest provides a planning tool that takes into account *some* value to the forest that goes beyond merely the value of the standing timber in the market.

Dollar-Based Valuation

Each choice of dollar-based valuation has limitations. How we place monetary value on natural capital reflects what we value and will necessarily be based on those values. Here are some methods that are used to value ecosystem services:

Market price method: Estimates economic values for ecosystem products or services that are bought and sold in commercial markets.

Productivity method: Estimates economic values for ecosystem products or services that contribute to the production of commercially marketed goods.

Hedonic pricing method: Estimates economic values for ecosystem or environmental services that directly affect the market price of some other good. Most commonly applied to variations in housing prices that reflect the value of local environmental attributes.

Travel cost method: Estimates economic values associated with ecosystems or sites that are used for recreation. Assumes that the value of a site is reflected in how much people are willing to pay to visit it.

Damage cost avoided, replacement cost, and substitute cost methods: Estimate economic values based on costs of avoided damages resulting from lost ecosystem services, costs of replacing ecosystem services, or costs of providing substitute services.

Contingent valuation method: Estimates economic values for virtually any ecosystem or environmental service. The most widely used method for estimating nonuse, or "passive use," values. Asks people to directly state their willingness to pay for specific environmental services based on a hypothetical scenario.

Contingent choice method: Estimates economic values for virtually any ecosystem or environmental service. Based on asking people to make trade-offs among sets of ecosystem or environmental services or characteristics. Does not directly ask for willingness to pay; this is inferred from trade-offs that include cost as an attribute.

Benefit transfer method: Estimates economic values by transferring existing benefit estimates from studies already completed for another location or issue (King and Mazetta, 2009).

Because they begin to apply comparable units to natural capital, the methods just listed are very helpful planning tools—they place values on services that have long been assumed and heretofore assigned little or no value in planning and policy. There can be great uncertainty in the numbers, so these methods are best used as internal planning tools, with careful explanation of assumptions and appropriate caveats to avoid confusion in over-applying them. Also, there will be variation even among the techniques used, so it is safest to calculate and quote the range of values generated by them. Working with a range of values prevents over-application of any one calculation and extrapolation of that value to conclusions that the numbers may not warrant.

3.3 ALIGN DRIVERS TO VISION AND MEASURES

Applying principles of ecological economics to the management of an organization will result in more forward-looking planning and will prepare the organization for the future. But these principles are even more potent as a planning tool as they become incorporated into public policy. There are a number of tools available to governments to implement ecological economics and allow market forces to work for, rather than against, sustainability, including the following:

- Subsidy shifting
- Fees
- Revenue-neutral tax shifts

3.3.1 Invest in What We Value: Subsidy Shifting

Once we have an accurate measure of prosperity—a measure that values what we value—we need to align our public investments with our vision:

Level the playing field. Apply "green scissors" to the budget (*http://www.green-scissors.com/*). At a minimum, government budgets should "first, do no harm" by phasing out subsidies for things we don't want or value—nonrenewable and polluting activities. A slow but steady phase-out of all perverse subsidies allows investment decisions to be made with certainty, but ending them ensures that sustainability leaders in each sector are not placed at a competitive disadvantage for their initiative and vision.

Invest public funds in what we value. To accelerate the transition to sustainability, it is wholly appropriate to invest our three capitals in the things we do value. This will put market forces to work for us rather than against us. Governments can subsidize responsible actions toward sustainability, such as

- *Establishing a revolving conservation loan fund* to finance the early capital costs spike of the transition to renewable energy and water-conserving equipment until the payback period ends and costs savings of sustainability are realized.
- *Developing a "first mover" policy* for investments that foster the first in a sector to develop sustainable practices. Here, too, the revolving loan fund set can help promote these investments.

3.3.2 Pay as You Go: Fee-Based Systems

All development and manufacturing activities should pay their true cost to society. If not paid up front, the costs are spread to third parties and/or passed on for future generations to deal with, distorting the market and limiting future prosperity. The ideal is to maintain protective laws against pollution and use fees on polluting activities to pay for the cost of monitoring and enforcement. Examples of this include

- Conservation pricing for water supply; and
- "Pay as you throw" systems for waste disposal, where you pay more as you waste more.

3.3.3 Tax Waste, Not Work: Revenue-Neutral Tax Shifting

The transactions that governments traditionally tax to raise revenue are not inherently bad: payroll and other income, property value, and sales volume. However, it would be much better to raise the same money on things that *are* inherently bad, like pollution and resource depletion. This not only incentivizes conservation and sustainability, but it also begins to recoup the societal costs of pollution and depletion that are not easily reflected in prices or fees, bringing accurate pricing into the market (Redefining Progress, 2009).

Tax shifts should be revenue-neutral, gradual but certain, and fair. They must also be no more regressive on lower-income people than present tax policy, and easily can be designed to be less regressive.

3.4 CONCLUSION

Nature operates in cycles, yet we humans have been living as if nature is always there, in a steady state, delivering biological services that make life itself possible. As we reach resource limits, we will face decision points at which the choice will be to determine what, rather than perpetual growth, makes us truly prosperous and, yes, even happy. At these points, when the bills come due for those unintended consequences of our rampant growth, we will look to ecological economics not as a chore, but rather as a path toward living in greater balance with natural cycles, and a way to stabilize that which sustains life itself—the climate, air, water and soil.

To be able to stabilize, we must first have a vision, then decide how best to measure progress toward our vision, and then align our priorities to support activities that move us toward the vision and discourage those that take us farther from it.

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PART

Introduction to Decision Consequence Analysis

II

William L. Hall

The better the logical basis for a decision, the more difficult it is for extraneous political factors to hold sway.

Howard, 1989

II.1 OBJECTIVE

This part presents a process and framework for sustainable decision making, along with examples of analytical tools for implementation. Its goal is to introduce a structured approach for building a decision-making model that recognizes uncertainties and is able to adjust in response to system feedback. The model provides a map for traveling from a flawed or unsustainable condition to a preferred sustainable condition in the future.

The next nine chapters discuss methodologies that can be used to overcome the hurdles that plague any attempt to advance the goal of sustainability in human activity. Achieving sustainability within our built environment, transportation infrastructure, and energy and resource supply systems is extraordinarily difficult, even when employing high-quality technical knowledge.

A variety of approaches are introduced for dealing with decision-making uncertainty. Addressing these uncertainties, especially when dealing with concepts of sustainability, often involves assembling and coordinating a complex array of inputs and outputs from a wide variety of disciplines. It also requires overcoming firmly held assumptions and ideologies on how the world and human systems should function and incorporating probabilistic analysis of actual consequences of various alternatives.

Sustainable systems are human or environmental systems that are capable of operating in harmony or in balance over time periods much longer than those usually considered for engineered systems in the past. Sustainability requires that a selected course of action, either in policy or specific infrastructure, not be static but instead be capable of responding and adjusting to feedback loops. Effective feedback and response mechanisms require

- Accurate and relevant data
- The capacity for decision makers to process and understand the data efficiently
- The capacity for decision makers to quantify, within the bounds of available knowledge and data, the limits of the consequences of different responses to environmental stimuli (i.e., data)

A framework for incorporating probabilistic analysis of outcomes is provided. This probabilistic assessment addresses the fact that it is impossible for an individual or decision-making group to acquire a robust *a priori* understanding of unintended consequences. A complete picture of the positive and negative feedback loops that may be set in motion by a particular set of decisions will always be elusive. However, a probabilistic understanding of the range of outcomes allows the construction of feedback mechanisms and performance metrics that can help to modify decisions as system feedback is measured and understood.

II.2 SUSTAINABILITY DEFINED

As defined by the federal government in Executive Order 13423 (2007), *sustainable* means

> *to create and maintain conditions, under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations of Americans.*

This definition is supported by the intergenerational definition of the Brundtland Commission (1987):

> *Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

Sustainability, as just defined, is a high, noble-sounding concept. It is often used by activists to try to constrain politically incorrect or distasteful activities. This is particularly true when those activities are not ones we are interested in or when we believe the costs of constraining them will be borne by others. The appeal of sustainability as a comprehensive decision-making framework lessens when it is applied to daily personal or business decisions. Noble intentions are difficult to maintain when the issues are complex and the benefits are vague, uncertain, and distant, but the costs are measurable, certain, and immediate. Thus, Executive Order 13423 and the Brundtland Commission statement are incomplete, as they only address a condition. A condition is neither sustainable nor unsustainable; it is merely a state of nature, likely fleeting, that is dynamically acting on and reacting to a variety of forces. Any model of sustainable decision making needs to incorporate the concept of system feedback loops. Feedback mechanisms that appropriately capture and allocate costs are the foundation of sustainability in human actions and decision making.

All organisms, from humans to microorganisms, are driven to survive and reproduce their particular sets of genes. To survive, organisms must capture and convert energy and resources at the lowest possible cost. The organisms most successful in this competition will pass their genetic packages and propensities on to the next generation.

For social species such as humans, an individual gains advantage from the higher efficiencies and survivability that arise from communal action. However, individuals, groups, businesses, governments, or nations can also gain survival advantages by offloading costs onto others, the commons (i.e., the public domain), or future generations. These offloaded costs include government deficits, greenhouse gas emissions, environmental damage due to industrial production, and the like. The inclination to let others bear costs can hamper the development of sustainable systems.

Any definition of sustainability is incomplete without recognition of the role of accurate allocation of costs. The expanded definition of sustainability, adopted in the decision consequence models discussed in the following chapters, is

> *to create and maintain dynamic feedback loops for decisions that accurately measure, allocate, and internalize costs in a manner that allows humans and nature to exist in productive harmony, while providing, within the unavoidable constraints of human nature, for the social, psychological, economic, and physical well-being of present and future generations.*

II.3 DECISION CONSEQUENCE ANALYSIS DEFINED

Decision Consequence Analysis (DCA) is the application of a formalized decision-making process that employs decision theory, probability, and statistics. The approach is specifically designed to enhance understanding and management of the uncertainty that is inherent in complex problems involving multiple disciplines within dynamic environmental systems. DCA has evolved out of the disciplines of systems research and game theory and out of research into cognitive processes. A decision problem is addressed by disaggregating uncertainties and identifying subjective beliefs about them. It includes computational techniques for predicting positive and negative outcomes and the utility of potential management approaches.

II.3.1 Structured Approach

DCA provides a structured model for mapping and evaluating possible outcomes and risks associated with decisions. The general strategy is to break down a complicated problem into increasingly smaller pieces until the particular component can be accurately analyzed and understood within the context of the overall problem.

II.3.2 Organization of Complex Problems

Decision Consequence Analysis provides effective methods for organizing a complex problem into a structure that can be more readily analyzed. For example, a problem is broken down into components addressing the possible courses of action, the possible outcomes, the likelihood of those outcomes, and the costs and benefits to be derived from them.

II.3.3 Addressing Uncertainty

DCA's most powerful component is its assistance to individuals or groups in collectively defining important sources of uncertainty and the nature of those uncertainties. It represents uncertainty in a systematic and useful way so that it can be better understood. In addition, it identifies uncertainties that can affect the validity of the decision outcome. For uncertainties that can alter outcome expectations, the technique provides a mechanism for decision-making groups, whether at the policy or implementation level, to define performance metrics, feedback loops, and conditional decision-making requirements.

II.3.4 Accommodating Multiple Objectives

Most environmental issues involve multiple objectives that may be internally contradictory. The achievement of one objective may diminish the achievement of others that are equally desirable. DCA provides a framework and specific tools for dealing with multiple objectives.

II.3.5 Respecting Different Perspectives

Some problems can become more difficult when different individuals or groups look at them from different perspectives or disagree on the uncertainty or value of the various outcomes. For example, environmental groups often have very different perspectives from those of developers or resource providers such as power companies, yet both views need to be considered during the design of a renewable energy project. The use of the DCA framework and tools can help sort through and resolve disagreements among groups of stakeholders with diverse opinions. Facilitated DCA® is further discussed in Chapter 21.

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CHAPTER

4 Barriers to Achieving Sustainability-Based Decision Making

William L. Hall

4.1 THE NATURE OF DECISION MAKING

We prefer to think that our individual or collective decisions, whether they are broad societal policy questions or individual choices such as which car to buy, are based on rational thought. “Rationality” can be difficult to define. The concept has a long and convoluted history in Western philosophy, but it describes a style of thinking and ordering our actions vis-à-vis our environment. The ancient Greek philosophers discussed the concept of rationality extensively. For them, it was the human ability to use logic, which was thought to be the hallmark of the gods. Rational thought was therefore the connection between the gods and humans. We might not have had the power of the gods, but we had the next best thing: the ability to create order in the world in the realm of thought.

Modern economics and, by extension, the decision making that dominates our lives, is built, or at least is thought to be built, on rational choice theory. This theory assumes that we make our choices by gathering data on alternatives and then choosing the alternative or set of alternatives that provides the highest utility, defined in this context as a measure of useful purpose or usefulness. Utility itself is a function of the probability of achieving a desired outcome times the value or expected pleasure or usefulness to be derived from it. Assuming we are rational economic creatures, economic theory predicts that we will make our choices based on maximizing our net expected pleasure.

Unfortunately, the simple model of rational choice theory succumbs to the unique way our minds work. Evolution has built a human mind that has distinct thinking patterns developed through natural selection in response to distinct survival needs. We need the ability to think rapidly, intuitively, and emotionally in response to danger, as well as logically and rationally in order to respond to complex long-term problems that involve the interaction of variables with consequences that may stretch over years and generations.

The emotional, instinctive component of our decision making serves us well in many situations. As the neuroscientist Joseph Le Doux said in his interview with John Brockman, “The advantage of [the emotional brain] is that by allowing

DOI: 10.1016/B978-1-85617-797-9.00004-6

evolution to do the thinking for you at first, you basically buy the time that you need to think about the situation and do the most reasonable thing." Emotional thought narrows our focus and screens out peripheral issues or stimuli. Our emotions prioritize input, giving us the ability to marshal our resources for an immediate task critical to our survival. Long-term, rational thinking is of little value if we are unable to survive the next minute (Brockman, 1997).

Many of our decision-making flaws are associated with the inability to control our evolved emotional brain, which selects only the data it perceives to be relevant to the immediate crisis. How do we control the emotional side of our brain in order to improve the quality of our decision making? Scientists who studied the people's brains while they played gambling games found a difference between subjects who consistently made rational responses and those who were swayed merely by the way the gambles were presented or framed. Both sets of subjects had the same amount of activity in the part of the brain that was responding emotionally to the way the problems were framed. The lead researcher, Benedetto de Martino (de Martino et al., 2006) explained, "We found that everyone showed emotional biases; no one was totally free of them."

The researchers did find a difference in activity in the prefrontal cortex. The higher the activity there, the greater the likelihood that a subject was able to resist the effect of how the problems were framed. This research demonstrated that those who were able to look past their irrational feelings could resist the mind traps that are built into our emotional patterns of responding to information. As stated by de Martino, "People who are more rational don't perceive emotion less, they just regulate it better."

The way to improve the quality of our thinking is neither overly complex nor elusive. We must be conscious of our emotional thinking patterns and understand how they affect our ability to rationally build decision-making models. The following sections provide an overview of the mind traps that affect the way we think and the way we respond to stimuli. Three general classes of barriers are discussed: conceptual models, psychological traps, and values versus alternatives.

4.2 THE ROLE OF CONCEPTUAL MODELS

A fundamental issue we face as individuals and societies is the extraordinary difficulty of altering long-held conceptual models of how the world works. Because of the huge amount of information we encounter at every moment of our lives, we must develop sets of assumptions about the way the world functions. These assumptions are developed primarily from experience rather than rigorous analysis of data.

Our assumptions may not be completely accurate or particularly robust, but if they prove functional, they become the basis for our understanding of the world. The longer the assumptions are functional and do not lead to unavoidable (and undeniable) collapse of some valued aspect of our lives, the more they solidify into habit, custom, tradition, or, at the extreme, various forms of fanaticism. When evaluated according to the current concept of sustainability, some of our conceptual models of how we should relate to the world as individuals or societies are shown to be inaccurate, incomplete, or insufficiently robust. But it is not easy to alter conceptual models; they have been successful according to some valued criteria.

In terms of material well-being, the societies built by the Western democracies following the Industrial Revolution have produced miraculous results. All but a very few citizens of these societies have a standard of living that would be inconceivable for even the aristocrats of the past. Western democracies, as a whole, engage in vastly less backbreaking labor, have more leisure time, and are better fed, better housed, better educated, and better entertained than those of two to three generations in the past could possibly dream.

Society-wide conceptual models for interacting with our environment (human and natural) evolve in response to the changes in and resulting pressures of the systems in which we live. Transformational changes in conceptual models occur when the environmental pressures reach a tipping point, at which the failure of existing models becomes too overwhelming to deny. As long as marginal adjustments at the fringes of our understanding of the world's functioning produce acceptable results, transformational changes are difficult, if not impossible, to achieve.

Two critical factors affect a modern society's ability to change. The first is the existing level of success as measured by the society's value system. A society's ability to alter the environment to maintain acceptable measures of success has a profound impact on its capacity to recognize and respond meaningfully to a changing reality. To a large extent, reality as we experience it can be managed for the short term. This ability delays the pressures that would otherwise force transformational change. The other factor is the time frame a society's conceptual model considers when making decisions. The relative value of any desire is time-dependent. A piece of marrow for a starving man today is much more important or valuable to him than a prime cut of beef a year from now. The relationship between decision making and time dependency is present within any sentient creature, but technology can severely exacerbate it by creating an over-dependency on shorter- and shorter-term expectations of benefit.

The importance of time frames is illustrated by the radical change in land management practices in North America over the last five centuries. Human attitudes regarding the land and its use have changed dramatically. Earlier in human history, the groups that were able to conscientiously manage the land and the human impact on natural resources were better able to survive. As the obvious link between a group's land use and its survival weakened, the conceptual model of the role of the land and its resources became more short term and exploitative.

One of the starkest examples of the effect of this shortened time frame can be seen in the changes in Appalachia that occurred during the late 19th and early 20th centuries. In a period of less than 100 years, ecosystems that that had persisted in balance since time immemorial were devastated. At the end of the 19th century, large tracts of land were acquired by corporations from outside the region.

Wholesale logging commenced and continued with little abatement until the 1920s. The rapidity of the destruction was staggering. As stated by Sharyn Kane and Richard Keaton in their 1993 book on the Southern National Forests:

> *Only tree stumps remained as far as the eye could see, as one great forest after another was indiscriminately logged with little thought of the consequences. Farmlands were equally despoiled. Unwise planting and harvesting practices had allowed crucial topsoil to erode and gaping gullies to form. Erosion was equally rampant where the original forests once stood. Without trees to hold soils in place, the ground washed away in great rivers of mud. Flooding increased, compounding the ruin, and the heavy silt in rivers and streams harmed water supplies and killed fish. Other wildlife also suffered as their habitats were destroyed. Uncontrolled hunting nearly eliminated white-tailed deer, black bear, and turkey in regions where they once numbered in the thousands.*

The control of large tracts of high-country forests by companies with no permanent connection to or dependence on the land allowed the forests to be viewed as a resource to be mined. There was profit to be made in the short term. The companies' conceptual model did not include a valuation for the forests' ability to prevent topsoil loss and flooding, protect water quality, and preserve ecosystems.

The result of the land use catastrophe in turn-of-the-century Appalachia was a large-scale exodus of Appalachian Scotch Irish communities to the southeastern Piedmont, looking for work in the low-paid, low-skill textile industry that had moved south from New England in search of cheaper labor. Thus, the dysfunctional conceptual model for understanding and valuing land-based resources directly contributed to a social upheaval that reverberates to the current day.

An evolving conceptual model of the role of society in long-term land use management ultimately led to the restoration of tens of millions of acres of destroyed ecosystems throughout Appalachia by the federal government, primarily through the Forest Service. But the change was controversial and tentative. Companies and their political allies objected to Theodore Roosevelt's intervention in what they judged the beneficent operation of the free market. By 1907 they had garnered enough support in Congress to force a revision of an 1891 law allowing government acquisition of "forest reserves" (Brands, 1997).

The exploitative conceptual model of land use that created the ecological disaster in Appalachia endures in the United States. The same short-term view, as well as resistance to alternative stewardship models, drives the growth of suburbia. The sustainable land use conceptual model, in which society creates the proper incentives for land stewardship, is in constant conflict with the exploitative conceptual model, in which society's role is to subsidize unfettered operation of the market. This exploitative model underpins the appeal of developmental highways, intentionally located to encourage or at least enable suburban sprawl, and it fuels political resistance to funding of land acquisition for protection of natural system infrastructure.

4.3 PSYCHOLOGICAL TRAPS

Since the time of Plato, it has been assumed that we make decisions by rationally organizing evidence and data and selecting a course of action. Extensive work over the last two centuries, though, has revealed common patterns of assessing information that are far from rational. These patterns have arisen as decision shortcuts for selecting courses of action rapidly and efficiently, and they are generally functional, or at least benign. Their persistence implies that, on average, their value in simplifying everyday decisions is at least marginally advantageous to survival.

Decision-making shortcuts evolved over millennia, during which human social organization advanced from simple tribal or clan structures to powerful multiethnic nation-states. Coupled with the growing complexity of social organization was the staggering increase in the power of an individual or a society to change the environment. The combined effect of these developments has been an exponential expansion in the potential consequences of a set of decisions.

Simply put, a set of bad land use decisions by a local warlord in 1000 B.C. regarding his village's spring planting could have been, and likely was, fully impacted by a host of irrational psychological traps. Regardless of their underlying irrationality, these decisions would produce acceptable results year after year, but eventually they would fail. The impact of the failure, however, would be limited.

By contrast, in our powerful, highly networked modern society, poor land use decisions may have an immediately dangerous impact. A federal policy regarding renewable energy that began in 2007 provides an example. The pressure to wean the United States off foreign energy sources created great interest in corn ethanol. The result was a set of policy initiatives that created incentives for growing more corn as well as incentives for the conversion of corn production from food to energy.

These decisions were made with many of the decision shortcuts that will be described in more detail shortly, such as anchoring, overconfidence, status quo, and confirming evidence. The decision makers did not conduct a thorough, rational analysis of the potential consequences of their decisions and did not consider the multiple influencing factors that might compound the magnitude of these consequences, such as farmer migration, drought, or increased consumption as far away as China. Policies were put into motion that created a host of unintended negative results. Land and crops were converted from producing food to producing energy, meat and grain prices rose, and pressure increased on limited water supplies in already stressed regions. To make matters worse, the policies did not even achieve their aim; they had little to no effect on greenhouse gases or foreign energy imports.

A similar example is Brazil's policy of energy independence, started in the 1970s. This policy contributed to rapid and devastating conversion of tropical forest, particularly in the southern reaches of the Amazon basin, to cultivation. This policy on its surface seemed unquestionably good. In the absence of a rational understanding of the potential consequences, though, it created a cascading set of unintended consequences. Given the power that exists in modern societies to alter their environments, there is a smaller margin of safety for irrational patterns of decision making. These patterns may have been functional, on average, in the past, but they can now be periodically devastating. Increased connectivity across cultures and economies makes data-driven decision making even more critical.

Homer-Dixon (2009) illustrated this point through comparison with natural processes inherent in ecosystems. As the level of "connectedness" increases, ecosystems become less resilient to perturbations and "align at the same phase of vulnerability." This alignment increases the chances of synchronized peaking and deep collapse. The best protection against the mind traps that prevent rational understanding of consequence is the awareness of the existence of such traps. For additional treatment of the characteristics discussed in the following paragraphs, see Hammond et al. (1999).

4.3.1 Status Quo

There is a bias toward decisions that perpetuate the current situation. Within any current paradigm, empirical evidence is available to help assess the standard set of alternatives. In addition, the status quo has authority from its mere existence. The longer a condition or situation exists, the more credibility it acquires, especially if it is seen as either part of, or inseparable from, the society in which it exists. Despite the potential long-term benefits that might be derived from changing the status quo, the built-in bias to maintain it can trump the best intentions unless there are clear, definable, and near-term financial incentives for change.

An example can be seen in the evolution of U.S. transportation policy. The federal government's involvement in providing comprehensive transportation infrastructure began with incentives for railroad construction in the 19th century. Although the railroads were developed by the private sector, significant government manipulation of market conditions encouraged and accelerated the creation of a continent-wide infrastructure.

The decisions to support railroad infrastructure were driven by very definable and near-term financial incentives. In addition, they were implemented within a status quo vacuum. Except in the immediate vicinity of cities and major towns, principally along the eastern seaboard, farm-to-market transportation was either very poor or limited to rivers. Moreover, it was complicated by the 1500-kilometer fall line, stretching from Georgia to New Jersey, which prevented goods from being shipped very far inland by river. Much of the interior was poorly served except in the areas populated enough to justify the construction of canals and locks for moving goods into and out of the upland interior.

A major change in federal government intervention came with the development of the Interstate Highway System. In 1921, the newly created Bureau of Public Roads, with the help of the Army, assembled a blueprint for a national network of roads, known as the Pershing Map, that could serve the country in a time of war. As automobile traffic increased, it became clear that a comprehensive system was necessary to supplement the United States Numbered Highway System, which was maintained by state and local governments and not a central authority. By the late 1930s, planning had expanded to a system of new superhighway corridors (McNichol, 2006). In 1956, the Federal-Aid Highway Act authorized the Interstate Highway System—a 41,000-mile network of highways that would link almost all cities with populations greater than 50,000 (Weingroff, 2006).

The Federal-Aid Highway Act of 1956 was a dramatic change in the status quo. Up to that point, the planning, coordination, and implementation of highways were almost entirely at the state and local levels. Throughout World War II the transportation of people and goods over significant distances was dominated by the railroads. After the war, however, several conditions converged to create powerful and highly focused financial incentives for changing the status quo. The most important were the availability of relatively inexpensive petroleum and the need for a market to absorb the manufacturing capacity that for a decade had been shaped by the needs of war. Although the highway system was justified in part as a component of national defense, it was heavily supported by the major U.S. automobile manufacturers.

A distinct choice was made by society to subsidize highways at the expense of the then-dominant means of moving large numbers of people (inter- and intra-city mass transit) and goods (heavy rail). Government subsidization of highways greatly aided those transportation developments and kept costs low. Railroads did not receive government assistance after the war. In fact, a wartime 15 percent excise tax on tickets, originally enacted to discourage civilian train travel, remained in effect, keeping fares higher than necessary. Reduced slightly in 1954, this tax was not completely removed until 1962. Government regulations, increasing municipal property taxes, and small towns using these property taxes to help subsidize new airports and local roads, added to expenses for railroads and hindered their ability to make improvements in passenger travel.

By contrast, the highway transportation infrastructure was and continues to be heavily subsidized. The initial cost estimate for the system was $25 billion over 12 years; it ended up costing $114 billion (adjusted for inflation, $425 billion in 2006 dollars) and taking 35 years to complete. Almost half of the construction and maintenance costs have been funded through general fund receipts, bond issues, and designated property and other taxes. The federal contribution (93.5 percent in 2003) is overwhelmingly from motor vehicle and fuel taxes, as is over two-thirds of the state contribution. However, local contributions are overwhelmingly from sources other than user fees (Federal Highway Administration, 2003).

This heavily subsidized system of infrastructure constituted a direct government subsidy to specific, favored sectors of the economy and to specific community organization patterns. The creation of the Interstate Highway System accelerated the conversion from a mass transport–dominated infrastructure to a car and truck–dominated system. It also led to government-incentivized social engineering on a massive scale. The resulting suburban sprawl, with its opportunity to physically separate racially and socio-economically and to create mass standardization in communities across the country, altered the physical pattern of human organization that had defined societies since the advent of the agricultural revolution. These patterns, until the 20th century, provided distinct boundaries between the country, farm, or forest edge and the village, town, or city.

Almost as soon as the Interstate Highway System began construction, there were concerns over its environmental and social costs. But an automobile-centric society became a deeply entrenched status quo. Huge commitments of public resources continue to be made to maintain the status quo transportation network. The debate regarding changes to the system is incremental at best. The 1950s level of commitment and vision that created the current transportation infrastructure is difficult to achieve for creating a sustainable transportation network that emphasizes optimizing energy efficiency while minimizing environmental and social damage.

The power of the status quo in this situation to skew the debate over sustainable practices is obvious in any discussion of the costs and benefits of the automobile over alternatives forms of transportation, particularly mass transit. Those coming of age after the 1940s can understand how the automobile affords mobility and the advantages of that specific type of mobility. What they may not be able to comprehend is the low-cost, efficient, near universal mobility offered to the public at large by the well-connected intra-city and long-distance rail and electric street car system that was ubiquitous across the United States prior to the heavy government and industry subsidies for their replacement. Virtually anyone with modest means could move about the country without the burden of the permanent fixed costs of owning and maintaining an automobile.

In addition, this mobility could be maintained with a fraction of the demand for finite resources of energy, land, or raw materials. It was a different type of mobility than that offered by the automobile. In many aspects it was more democratic and socioeconomically neutral in its accessibility. In terms of sustainability, it was vastly superior to the current auto-centric system. To understand this point, imagine how the oil embargo of the 1970s, with its endless lines at gas stations, would have affected the country if the transportation infrastructure of the 1940s had still been in place.

The burden of the status quo is that it is difficult to generate public support for transformational policies that will take decades to implement. The benefits of an automobile-centric world can be seen. The benefits of a fully balanced transportation system are speculative. The result is that truly transformational restructuring of the transportation system must overcome a status quo in which alternative transportation is little more than a supplement to what already exists.

4.3.2 Sunk Cost

Closely related to the issue of status quo is that of sunk cost. Skinner (2001) defines sunk cost as the money already spent on a project. Since it has already been spent, it should not be relevant to decisions about further spending. The issue of sunk cost can become extremely emotional, as decision makers become invested in past decisions and fail to recognize the failure to achieve current objectives. Although it is difficult, decision evaluations should never consider sunk costs, but only the forward path to achieving success. As Will Rogers famously said, "When you find yourself in a hole, stop digging."

In environmental remediation or restoration, the issue of sunk cost most often arises when progressing from an interim to a final remedy. Interim remedies are driven by the immediate and rapid need to address the completion of a risk pathway and prevent the potential exposure of a human or ecological population to a contaminant. Final remedies are selected after this immediate need for protection has been addressed, and when the objective has become final cleanup and long-term maintenance. Although the selection of either an interim or a final remedy is based on technical evaluation of the release, identification of the receptor populations, and knowledge of contaminant concentrations and migration, their ultimate goals are very different.

For example, consider the case of a groundwater plume that has migrated from its source off the owner's property and has the potential to impact a drinking water aquifer used by down-gradient residents. An appropriate interim remedy would be to intercept the flow at the leading edge and prevent the contamination of the drinking water source. However, if this is carried out over several years and is never adjusted to address the source of the release, the situation is exacerbated since the contamination will continue to move away from the source, and may even be pulled toward any system that is trying to intercept the contamination. The result could be that the short-term intervention may stop the contamination from reaching a receptor, while simultaneously resulting in a greater mass of contamination moving closer to the receptor. The ultimate result could be that the short-term intervention makes matters worse over time, continually pulling contamination toward the residents.

The rationales for which remedy is selected, where it is placed, and what is monitored are completely different for interim versus final remedies because the objectives are not the same. However, in many cases decision makers are reluctant to alter the remedies selected as interim measures, and instead push for their continued use as final remedies primarily based on the emotional connection to the initial, interim remedy decision. They have often expended several millions of dollars in capital investment and spent years watching the system operate efficiently. Despite the emotional connection, however, these factors have no bearing on the path to final cleanup. Chapter 21 provides a detailed description of a Facilitated Decision Consequence Analysis (DCA) used to assist in moving a project from an interim to a final remedy.

4.3.3 Anchoring

Anchoring is the tendency to give disproportionate importance to the first information received. Given the huge amount of data that inundates our senses on a continuing basis, we need a way to organize and cull it into recoverable blocks of information. This capacity is essential; without it, we would be too overwhelmed with information to make decisions. As soon as we start considering information regarding an issue or decision under consideration, our brains begin to construct a data organizational pattern, or filing system. The first information in the filing system forms the foundation on which subsequent data is organized. The mind trap is that the first information received may be completely irrelevant, if not completely wrong.

The brain's tendency to anchor on early information in a decision is demonstrated by a study conducted by a group of MIT economists led by Dan Ariely (Ariely et al., 2003). The group conducted an auction of a random group of items with business school graduate students. The auction had a unique component: prior to the bidding the students were asked to write down the last two digits of their Social Security numbers. They were then asked to indicate whether or not they would be willing to pay that specific amount of money for each of the auction items. Following this exercise, they were asked to indicate how much they would be willing to actually pay for the items.

The last two digits of a person's Social Security number should have no impact whatsoever on what he or she is willing to pay for an item. Despite this irrelevancy, the group of presumably intelligent and rational graduate students was clearly influenced by the initial focus on these digits. On average, students with high numbers offered 300 percent more for a given item than students with low numbers.

The connection of a Social Security number to the decision-making process was not a result of physical relevancy but of temporal relevancy. The digits were introduced at the beginning of an active decision-making process. The items in the auction were random and not ones that the students would frequently buy or otherwise have extensive, recent points of reference for. In the absence of an available frame of reference, the mind begins to build one with the material or information at hand.

The impact of anchoring is evident in the regulatory framework for decision making in the management of environmental risk. As defined in the National Oil and Hazardous Substances Pollution Contingency Plan, the point of departure for assessing hazardous waste sites is an incremental risk of 1×10^{-6} (NCP, 1994). This means that for every 1 million people, one additional individual will contract cancer because of the contamination under investigation. This incremental risk is typically calculated over a lifetime, assuming an extended period of exposure to the environmentalfactor.

The problem with this number is that it anchors the decision-making process on what may be a completely inappropriate measure of success for managing a particular risk. The effort to manage an environmental concern can become completely warped by the focus on achieving the 1×10^{-6} incremental risk. Anchoring on this value, with little critical questioning of its reasonableness, can alter decision making dramatically. This anchor can often impede the goal of creating sustainable human interaction with environmental systems.

The data shown in Figures 4.1 and 4.3 demonstrate the impact of this anchor on rational decision making. Figure 4.1 provides a representative list of the actions that increase the risk of dying by 0.000001 and their respective causes (Wilson, 1979). As shown, a 1×10^{-6} incremental risk is vanishingly small. But without context it is difficult if not impossible to assess what is meant by "vanishingly small." An effective tool for understanding relative risk is the risk ladder prepared by Robert Cameron Mitchell of Clark University (Mitchell et al., 1986 shown in Figure 4.2.

At the time of Mitchell's work, approximately 2.2 million persons in the United States died each year out of a population of 250 million, giving an overall

Actions	Cause
Drinking 1 pint of wine	Cirrhosis of the liver
Living 2 days in New York or Boston	Air pollution
Traveling 10 miles by bike	Accident
Traveling 300 miles by car	Accident
Flying 1000 miles by plane	Accident
Flying 6000 miles by plane	Cancer caused by cosmic radiation
Living 2 months in stone or brick building	Cancer caused by natural radioactivity
One chest X-ray taken in a good hospital	Cancer caused by radiation
Living 2 months with a cigarette smoker	Cancer, heart disease
Drinking 30 12-oz. cans of diet soda	Cancer caused by saccharin
Living 150 years within 20 miles of a nuclear plant	Cancer caused by radiation
Eating 100 charcoal-broiled steaks	Cancer from benzopyrene
Living 2 months in Denver on vacation from New York	Cancer caused by cosmic radiation
Eating 40 tablespoons of peanut butter	Liver cancer caused by aflatoxin B
Drinking Miami drinking water for 1 year	Cancer caused by chloroform
Smoking 1.4 cigarettes	Cancer, heart disease
Spending 3 hours in a coal mine	Accident

FIGURE 4.1

Actions that increase the risk of dying by 1 in 1 million.

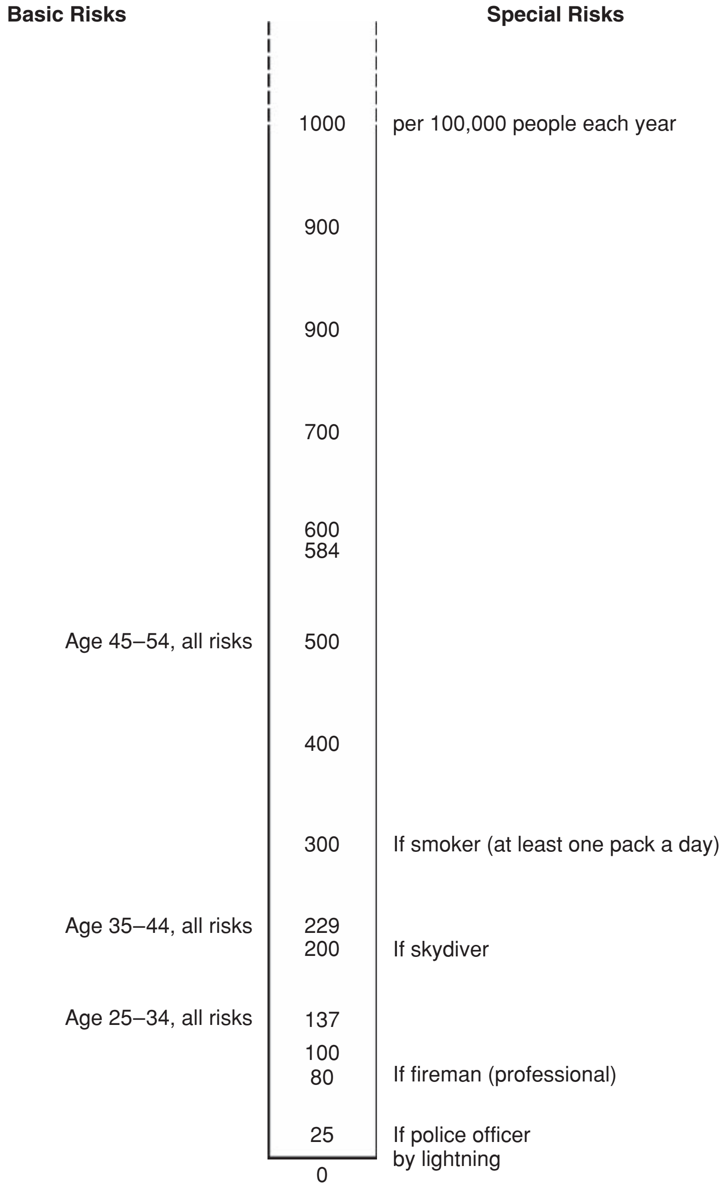

FIGURE 4.2A

Risk ladder for annual risk of dying.

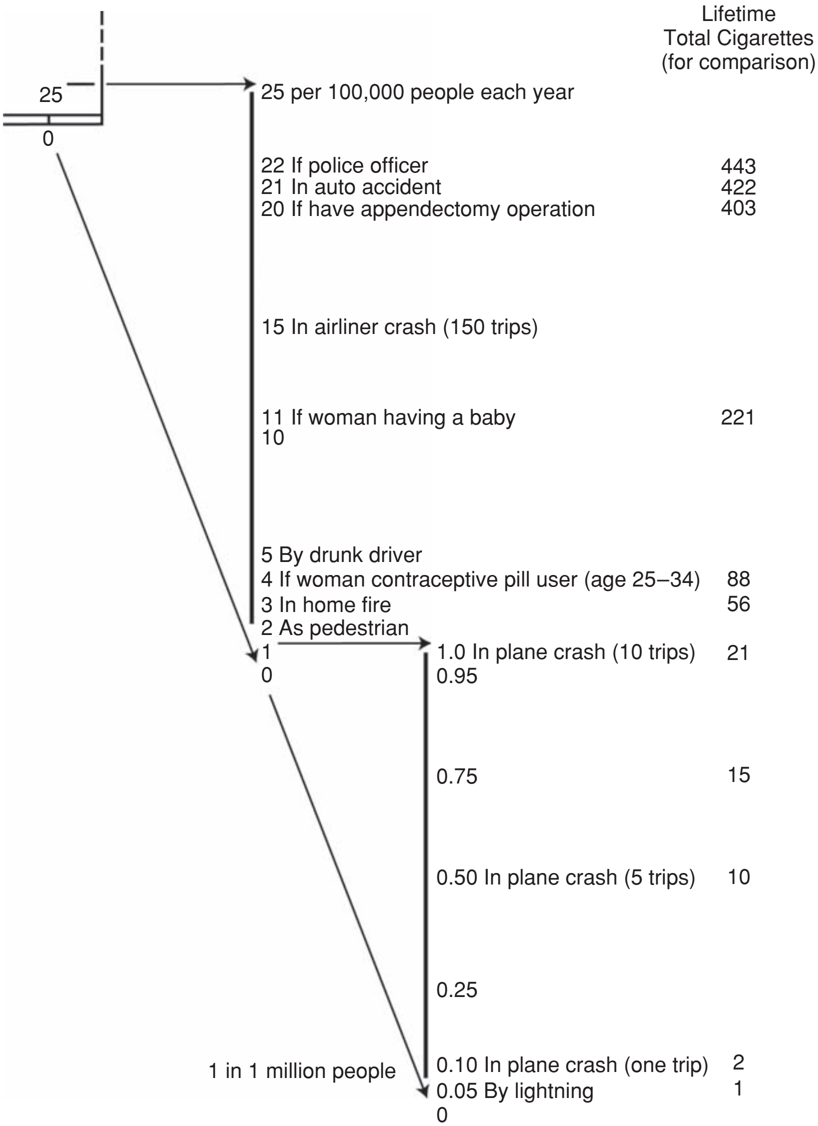

FIGURE 4.2B

Risk ladder—lower-level risks (annual).

mortality risk of 1,000 out of every 100,000 persons (as shown at the top of Figure 4.2). The risk of mortality can be refined based on additional information, the most significant being age. A young adult 25 to 34 years of age on average has a 137 in 100,000 risk of death in any given year. By the time he or she reaches middle age, the risk of death on average rises to 584 per 100,000.

These numbers translate into 1,370 and 5,840 persons, for each age group respectively, per year for every 1 million individuals.

Now examine, in context, the one-in-a-million lifetime incremental risk of contracting cancer that is used as the anchor for establishing the significance of a particular environmental risk factor. Even without exposure to environmental contamination, an individual's risk of dying will gradually rise from 1370 per million to over 7500 per million by the time he or she reaches age 60. This baseline risk of dying shows the insignificance of an incremental risk of contracting cancer of one per million individuals over a lifetime. The anchor could have been either number—the 7500-per-million risk of dying per year or the one-in-a-million chance of contracting cancer over alifetime. Either can lead to poor decision making and poor allocation of resources for problem solving. The critical issue is the understanding the impact of anchors and the need for context.

The importance of this context for sustainable decision making is demonstrated with Figure 4.3 (Tengs et al., 1995). The information was derived from a Harvard University Center for Risk Analysis survey of public initiatives or interventions. The areas investigated covered medical, residential, transportation, occupational, and environmental aspects of society. The results demonstrate astounding differences in the cost of achieving extra life years, with standard environmental interventions standing out with a staggeringly high $4.2 million per additional life year achieved.

As discussed in more detail in a following section on the Precautionary Principle, many want to argue that there should be no cost limit on saving a life. However, this argument ignores the environmental impact of incremental costs. The generation of the $4.2 million requires economic activity. The resources to pay for incremental costs have to come from somewhere, and they are coming from a finite pool of discretionary income. For example, assume that 10 percent of the economic productivity in the United States is discretionary wealth, which in this example is taken to mean resources that can be targeted to general improvement of our social or environmental conditions. This wealth is in contrast to resources that must be expended for water, food, shelter, security, basic health care, transportation, and so forth, to survive and thrive on a daily basis.

With this assumption, over $40 million in economic activity would be needed to produce the $4.2 million needed to save one life year. According to the U.S. Census Bureau, the medium U.S. household income in 2007 was $50,223 per year. With the assumption that 10 percent of each family's income is discretionary as just defined, it would require the wealth produced by 800 families over an entire year to achieve the one-life-year reduction in risk.

The issue is not the value of a life and whether or not 800 families should dedicate all their discretionary income each year to providing this hypothetical one-life-year risk reduction. Instead, it is a question of thoughtful, comprehensive, and balanced decision making in the allocation of resources to create sustainability in our social and environmental support systems.

Interventions	Cost per Life-Year
Federal law requiring smoke detectors in home	< $0
Reduced lead content of gasoline from 1.1 to 0.1g per leaded gallon	< $0
Measles, mumps, and rubella immunization for children	< $0
Mandatory seat belt use laws	$69
Influenza vaccination for high-risk people	$570
Chlorination of drinking water	$3100
Annual mammography and breast exam for women age 35–49	$10,000
Heart transplant for patients age 50 with terminal heart disease	$10,000
Improve basic driver training	$20,000
Benzene exposure standard of 1 versus 10 ppm in rubber and tire industry	$76,000
Dioxin emission standard of 5#/air dried ton of pulp	$4,500,000
Radionuclide emission control at elemental phosphorous plants	$9,200,000
Arsenic emission control at glass manufacturing plants	$51,000,000
Radiation emission standard for nuclear power plants	$180,000,000
Benzene emission control at rubber tire manufacturing plants	$20,000,000,000

FIGURE 4.3

Cost efficiency in saving life for selected interventions, with cost per life year saved in 1993 dollars.

4.3.4 Confirming Evidence

The mind trap of confirming evidence is the tendency to seek or only see the data or information that supports what we already believe. This tendency can be readily seen in political debate. Arguments for or against various policies such as health care often reference the experience of other countries with differing degrees of socialization of the health care system. The data referenced, though, are selectively culled depending on which policy position is being defended.

Health care costs have been rising steadily for years. In 2006, U.S. health care spending was about $7,026 per resident and accounted for 16 percent of the gross domestic product (GDP). Total health care expenditures grew at an annual rate of 6.7 percent in 2006, and though it was slower than in recent years, it still outpaced inflation and the growth in national income (Catlin et al., 2008).

Although Americans benefit from this increasing investment in health care, the recent rapid cost growth, coupled with an overall economic slowdown and a rising federal deficit, is placing great strains on the systems that finance health care, including private employer-sponsored health insurance and public insurance such as Medicare and Medicaid. Since the year 2000, employer-sponsored health coverage premiums have increased by 87 percent (Kaiser Family Foundation, 2007). Employers are increasingly shifting costs to their employees in the form of higher premiums, deductibles, and co-payments. With workers' wages growing at a much slower pace than health care costs, many face difficulty in affording this increase in out-of-pocket spending.

Some of the major factors driving the costs in the U.S. health care are the intensity of services, prescription drugs and technology, an aging population, and administrative costs. All of the industrial nations are facing the same problems. The search for a solution is strongly affected by which part of the problem is considered most central. That, in turn, is heavily influenced by prior convictions brought into the analysis.

A striking example of the use of confirming evidence in policy debate is the attitude toward the role of government versus the private sector in the delivery of health insurance and the management of health care. The debate centers on two major issues: the efficiency of public and private systems and the prospect of rationing.

With respect to administrative costs, public systems in the United States have shown themselves to be more efficient. Overall, 7 percent of health care expenditures go toward administrative costs (e.g., marketing or billing), but this portion is much lower in the Medicare program (less than 2 percent), which is operated by the federal government (Kaiser Family Foundation, 2005). With respect to delivery of service, no country has or can resolve the issue that, ultimately, health care is rationed. Rationing may arise from the absence of resources on the part of individuals (i.e., the uninsured in the United States) or institutional rationing on the part of either insurance companies or governments.

Those on the right of the policy debate overlook these facts and appeal to the existing aversion Americans have to large government institutions. An example is a statement from Robert E. Moffit, Director of Domestic Policy Studies at The Heritage Foundation (Moffit et al., 2001):

> *If you insist on government management of the health care system, do not expect freedom from waste, inefficiency, or inequity in the delivery of care (look at France). … If you want to promise citizens a national or state program of universal insurance coverage, don't expect that you will be able to deliver*

> *universal access to high-quality health care. You won't and you can't (look at Britain). … If you want to fix prices for medical services, prescription drugs, or other medical devices, don't expect demand for these goods and services to be met or investment in research and development to continue apace. It won't (look anywhere). … If you insist, with a straight face, that in a government-run health care system, all of your fellow citizens will be treated equally—regardless of their class, station in life, or disease condition—you are not merely enthusiastic or well intentioned. You are lying.*

Moffit's statement appeals to preconceived notions about large government institutions. It looks only at the flaws that exist in other systems and does not consider the flaws in the U.S. system or the overall success and efficiency of European systems. A counter to Moffit's argument is provided by the McKinsey Global Institute (2007), which observed that the United States has $480 billion in excess health care spending each year in comparison to Western European nations that have universal health insurance coverage. These costs are mainly associated with excess administrative costs and poorer quality of care. The same report also observed that the United States spends six times more per capita on the administration of health care than its peer Western European nations.

The point is not to argue which view is correct, but rather to show that selective use of data and information is a ubiquitous problem in comprehensive problem solving. The same problem exists when addressing many of the complex sustainability issues that we face as a nation. These issues have the same level of multidisciplinary complexity, coupled with the uncertainty and difficulty in obtaining and vetting the data underlying the ultimate decision. Our decisions can be immeasurably improved, though, when we are fully aware of our tendency to justify our preconceived notions and are able to overcome those biases.

4.3.5 Framing and Mathematical Probabilities

The way a problem is framed can have a huge impact on the way we respond and make decisions. People are risk-averse when a problem is posed in terms of gains but risk-seeking when a problem is posed in terms of avoiding losses. This typical emotional response can lead the most rational individual to make a flawed and foolish decision.

The impact of how a problem is framed is exacerbated by the difficulty that virtually everyone has, even highly educated individuals in quantitative disciplines, with understanding probabilities. People consistently underestimate large probabilities and overestimate small ones. In addition, it is very difficult to detect inconsistencies in reasoning.

An example of this problem was described by Jonah (2009). A group of physicians were asked to decide on a course of action for a hypothetical outbreak of a rare disease, in which, it was assumed, six hundred people would die. Two alternative courses of action were proposed in which the exact scientific consequences could be quantified:

- **Alternative A.** Two hundred people would be saved.
- **Alternative B.** There was a one-third probability that all six hundred of the expected victims would be saved and a two-thirds probability that all would die.

Seventy-two percent of the physicians chose option A, which seemed to be the certain approach. It appeared that a guarantee that at least two hundred people would be saved was preferable to taking the gamble that no one would be saved.

Now let's phrase the problem differently. We are dealing with the same scenario of a disease outbreak but with these alternative courses of action:

- **Alternative C.** Four hundred people would die.
- **Alternative D.** There was a one-third probability that no victims would die and a two-thirds probability that six hundred would die.

When the problem was posed to a group of physicians in this manner, they reversed their previous preference. In this case, 78 percent of the physicians chose option D, which was the less certain of the two.

The reversal doesn't make any sense on the surface. The expected outcome of each of the alternatives is shown in Figure 4.4. All of the alternatives had the same expected outcome. The expected survival (number of victims × probability of survival) was two hundred individuals in all cases. The only difference was how the question was posed. Between options A and B, the choice was between a certain gain and a gamble. In contrast, between options C and D, the choice was between a certain loss and a gamble.

In the experiment, when the choice was phrased in terms of a certain gain versus a gamble, the gain was preferred. However, when the phrasing was reversed and expressed in terms of a certain loss versus a gamble, the gamble was selected, although there was no difference in outcome between options A and B or between options C and D.

Option	Survival		Mortality		Expected Survival Result
	Number	Probability	Number	Probability	
A	**200**	**100.0%**	**400**	**100.0%**	200
B	600	33.3%			200
			600	66.70%	
C	200	100.0%	**400**	**100.0%**	200
D	600	33.3%			200
			600	66.7	

FIGURE 4.4

Probabilities of alternatives.

The hardwired flaw in our reasoning, which is known as "loss aversion," was first demonstrated in research conducted by Daniel Kahneman and Amos Tversky (1979), who uncovered a pattern of decision making that seemed to be governed by the preference to avoid loss. They observed that the pain of loss was approximately twice as potent as the pleasure generated by gain. Most important, though, they observed that decisions seem to be governed by these feelings as opposed to rational, analytical thought.

Coupled with the mental habit of loss aversion is the difficulty we have in accurately relating to or understanding the interaction of probabilities. Bayesian conditional probabilities can be especially difficult to grasp. Eddy (1982) described an experiment in which physicians were asked to estimate the probability that a patient with a lesion had cancer. Initial examination indicated a 99 percent probability that the patient's lesion was benign. A subsequent X-ray gave a positive result for malignancy. The X-ray could correctly identify 79.2 percent of all malignancies and 90.4 percent of all benign lesions.

This type of information is analogous to the physical, biological, or geochemical information that is available in environmental systems analysis. Variability exists in environmental data collection, and there is always a possibility of false positives and false negatives. The challenge is determining the probability of a particular outcome, in this case whether or not the patient has cancer in light of the apparently contradictory information from the negative examination and the positive test.

The solution to the problem was introduced in a book by a Presbyterian minister, Thomas Bayes of Tunbridge Wells, England, called *Essay towards Solving a Problem in the Doctrine of Chances*, posthumously published in 1763 (McGovern, 2003). Bayes investigated the idea of statistical inference and developed a methodology for estimating the probability of an event from the frequency of its previous occurrences.

Bayes's formula takes the form shown in Figure 4.5. $P(D)$ is the *a priori* probability of witnessing the data D under all possible hypotheses. Given any exhaustive set of mutually exclusive hypotheses H_i, we have Figure 4.6.

$$P(H|D) = \frac{P(H|D) = P(H)}{P(D)}$$

Where

- *H* is a hypothesis, and *D* is the data.
- $P(H)$ is the *prior probability* of *H*: the probability that *H* is correct before the data *D* was seen.
- $P(D/H)$ is the conditional probability of seeing the data *D*, given that the hypothesis *H* is true. $P(D/H)$ is called the *likelihood*.
- $P(D)$ is the marginal probability of *D*.
- $P(H/D)$ is the *posterior probability*: the probability that the hypothesis is true, given the data and the previous state of belief about the hypothesis.

FIGURE 4.5

$$P(D) = \sum_i P(D, H_i) = \sum_i P(D|H_i)P(H_i)$$

FIGURE 4.6

As applied to the situation with the patient with contradictory information regarding the likelihood of cancer, $P(H|D)$ is the probability that the lesion is cancerous given the available data. The prior probability, $P(H)$, from the initial examination was 0.01. The X-ray has a 79.2 percent probability of accurately identifying the lesion as cancerous if it actually is cancerous. This is the conditional probability, $P(D|H)$. The numerator is therefore (0.792 × 0.01) = 0.00792.

The denominator is the a priori probability of witnessing the data D under the entire set of possible hypotheses. Remember, the a priori test indicated a 1 percent chance that the lesion was cancerous and a 99 percent chance that it was not. If the lesion was benign, the second test had a 9.6 percent chance of misidentifying it as cancerous. Therefore, the denominator is the total probability of identifying the lesion as cancerous. This is the sum of the probability that it is cancerous and correctly identified as such in the second test and the probability that it is noncancerous but incorrectly identified as cancerous in the second test:

$$(0.01 \times 0.792) + (0.99 \times 0.096) = 0.096$$

The probability that the tumor is actually cancerous is therefore

$$0.00792/0.096 = 0.077 \text{ or } 7.7\%$$

Contrary to the actual probability that the lesion was cancerous, over 95 percent of the study group of physicians provided a subjective probability of approximately 75 percent that the lesion was cancerous. They misjudged the probability by an order of magnitude. In this case, the consequences for decision making would be serious, as they would likely affect a physician's ability to accurately balance the benefits and risks of various forms of intervention.

Despite the data available for assessing the problem, the physicians almost universally failed to adopt an analytical strategy for doing so. The 75 percent probability chosen by the physicians was remarkably close to the 79.2 percent probability of the lesion being cancerous from the second test. The physicians appeared to anchor on the 79.2 percent, (as, in fact, many later admitted) and use it as a heuristic for arriving at a solution to the problem.

Why does Bayes's theorem give such a different number from what appears to be the obvious 79.2 percent probability of the lesion being cancerous? The insight of this theorem is that there are many more benign lesions than malignant ones in the population as a whole. Assume that 1000 individuals with lesions go through the testing. Of this number only 1 percent, or 10, will actually have cancer; the remaining 990 will not. If all 1000 are then subjected to the second test, approximately 8 of the 10 (79.2 percent) who actually have cancer will test positive. However, 9.6 percent, or approximately 95 of the 990 who don't have cancer, will also test positive. Therefore, a total of 103 individuals will test positive, whereas only 8 will be truly positive for cancer.

What is the significance of Bayes's theorem in developing policies that promote sustainability? The simplest answer is that a fuller understanding of probabilities can help put data in the appropriate context to support decision making. In the environmental debate, positions or claims are often based on extremely short-term trends. For example, a single wet or dry year or even a string of years does not provide the basis for long-term decision making regarding the ability of a particular watershed to support agriculture or other human uses.

An example of data taken out of its larger context can be seen in the discussion of grain yields and global warming in debates over energy, transportation, or water use policies. Lester Brown and Hal Kane (1994) claimed that grain yields were either no longer increasing as fast as they had in the past or had even stopped increasing. In refuting predictions from the World Bank regarding grain yields, Brown and Kane stated, "From 1990 to 1993, the first three years in the Bank's 20-year projection period, worldwide grain yields per hectare actually declined." They claimed that we were reaching the physiological limits of the plants.

Yields did decrease from 2.51 tons/hectare to 2.49 tons/hectare, but this observation neglected the *a priori* quantitative as well as the critical *a priori* qualitative information. As pointed out by Lomborg (2001, p. 8):

> *While Brown's claim is technically true (the grain yield did decline from 2.51 t/ha to 2.49 t/ha), it neglects and misrepresents the long-term growth. Moreover, it ignores the fact that this decline did not take place in the more vulnerable developing countries, where yields have steadily grown. Actually, the reason Brown finds grain yield declines in the early 1990s is primarily due to the breakup of the Soviet Union, causing grain yields there to plummet, but this is hardly an indication of physiological limits of the plants.*

In fact, as of 2007, coarse grain yields had increased to over 3.5 tons/hectare (Food and Agriculture Organization, n.d.)—an almost threefold increase over 1961 yields and a 40 percent increase over yields in 1993, when a short-term record was used by Brown to argue that yield had reached a plateau in 1990. As can be seen in Figure 4.7, the overall pattern of grain production is one of a steady increase, with the periodic variability expected in any environmental system. Focusing on short-term variability without consideration of the *a priori* quantitative and qualitative data provides a poor basis for decision making.

The problem with reliance on short-term trends can be seen in later claims by Brown. In a 2003 article, he discussed the significance of the heat wave that affected Europe in the summer of that year, connecting the heat wave to global warming and both to a declining trend in grain production. His article created the impression that worldwide grain production would continue to correlate inversely with global warming trends. According to Brown:

> *With this year's drawdown, world grain stocks have dropped to the lowest level since the early 1970s. When world grain stocks dropped to a dangerously low level in 1973, world prices of wheat and rice doubled.…*
>
> *As atmospheric carbon dioxide (CO_2) levels climb higher each year in an unbroken ascent, they are creating a greenhouse effect, raising the earth's temperature. Over the last quarter century the earth's average temperature has risen 0.7 degrees Celsius or more than 1 degree Fahrenheit. … If rising temperatures shrink harvests and drive up food prices, consumer pressure to reduce the use of fossil fuels will intensify. Indeed, rising food prices could be the first global economic indicator to signal the need for a fundamental shift in energy policy, one that would move the world toward renewable energy sources and away from climate-disrupting fossil fuels.*

As shown in Figure 4.7, drops in grain production from one year to the next occurred at least 10 times in the 30 years prior to 2002–2003. Moreover, several were as severe or more so than the 2003 decrease. The correlation between worldwide decreases in grain production and temperature was weak. Additionally, since 2003 grain production has increased by almost 20 percent despite a continuing increase in worldwide temperature.

This is not to say that global warming is not a problem or that there are no environmental issues connected with food production. Rather, it points out the need to examine our environmental policy issues with an understanding of

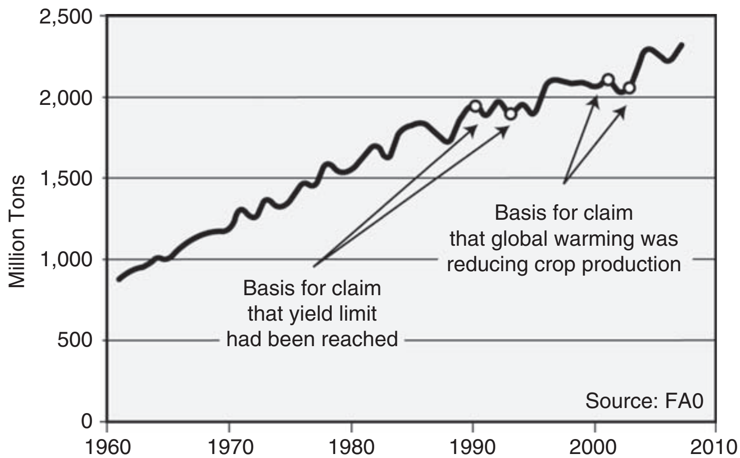

FIGURE 4.7

World grain production, 1961–2007.

Bayesian probabilities. There will always be contradictory indicators in our attempts to understand the consequences of decisions, and our data will be imperfect. The comprehension of true probabilities, though, will increase our capacity to make decisions that foster sustainable human and environmental systems. It is awareness of the complexities within the data that allows us to protect against the tendency that Oliver Wendell Holmes (1912) observed: "Most people think dramatically, not quantitatively."

4.3.6 Prudence, or the Precautionary Principle

Prudence is the tendency to slant probabilities and estimates "to be safe," thus potentially cascading to the creation of huge costs with little practical benefit. This tendency has its clearest manifestation in the Precautionary Principle. As outlined by Julian Morris in *Rethinking Risk and the Precautionary Principle* (Morris, 2000), the Precautionary Principle, or PP, can be traced to German environmental policy in the mid-1970s, which was based on the principle of *Vorsorgeprinzip*, or foresight planning. This principle made a distinction between human actions that cause "dangers" and those that merely cause risk. Intervention on the part of government is necessary at all costs to prevent danger, whereas risk should be managed with preventive action.

The PP concept began to appear in the United States after the Second World War. As described by Morris, it was the basis for major policy disputes, including the debate over fluoride and nuclear power. The resistance to fluoride originated from the right wing of the political spectrum, with conservatives arguing that fluoride was used as a rat poison (obviously in much different doses), fluoridation was mass medication, and government intervention was an inevitable slide into socialism. Given the risk, no amount of benefit could justify fluoridation of drinking water supplies.

Nuclear power was resisted from the left of the political spectrum. It was known that high exposure to nuclear material carried serious risks and that it could pose significant dangers if misused. The catastrophic consequences of an accident were the basis for opposing the technology, despite its benefits.

The international standard definition of the PP was adopted in the Ministerial Declaration of the UN Conference on Environment and Development (the "Earth Summit") in Rio de Janeiro in 1992 (U.N. Environment Programme, 1992):

> *In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.*

The Wingspread Conference on the Precautionary Principle was convened by environmentalists in January 1998 to develop their own definition of PP. The meeting took place at the Wingspread headquarters of the Johnson Foundation in Racine, Wisconsin, and involved some three dozen scientists, lawyers, policy makers, and environmentalists from the United States, and Europe. The attendees developed their own definition of the PP:

> *Therefore, it is necessary to implement the Precautionary Principle: When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically. … In this context the proponent of an activity, rather than the public, should bear the burden of proof. … The process of applying the Precautionary Principle must be open, informed and democratic and must include potentially affected parties. It must also involve an examination of the full range of alternatives, including no action.*

To support the need for the Precautionary Principle, the statement from the Wingspread Conference cited a range of health problems, from cancer to learning deficiencies, that are caused at least in part by the use of toxic substances, exploitation of natural resources, and changes to the environment. The statement implied that existing regulatory systems are insufficient and that modern society and its social mores for protecting the environment are demonstrably failing.

There are two flawed assumptions in the Wingspread rationale for the Precautionary Principle. The first is the assumption that current regulatory policies are failing and causing a rise in health problems and ills. The second is the assumption that these risk-bearing activities occur in isolation and have no counterbalancing effects or offsetting decreases in risk. The robustness of the first assumption can be tested. An example of the thinking of the Wingspread Conference is found in the popular scientific book *Our Stolen Future* (Colborn, 1996), which states, "By far the most alarming health trend for women is the rising rate of breast cancer, the most common female cancer." It goes on to link this alleged increase with the expansion of the chemical industry beginning in the 1940s:

> *Since 1940, when the chemical age was dawning, breast cancer deaths have risen steadily by 1 percent per year in the United States, and similar increases have been reported in other industrial countries. Such incidence rates are adjusted for age, so they reflect genuine trends rather than demographic changes such as a growing elderly population.*

Given that a 1 percent increase per year since 1940 would have produced a near doubling of breast cancer deaths by 2004, this claim is unequivocally wrong. In fact, as shown in Figure 4.8, from the American Cancer Society (2009), the death rate from breast cancer has actually dropped since 1940 by almost 20 percent. The incidence rate, a measure of the number of newly diagnosed cases each year, is separate from the death rate. Because medical treatments improve, the death rate can drop even if incidence increases. Consistent incidence rates are not available as far back as 1940, but available data shows that, while breast cancer incidence did increase from the 1970s to the 1990s (though not as steadily as Colborn claims), it fell significantly, at a rate of 2.2 percent per year, from 1999 to 2005 (American Cancer Society, 2009).

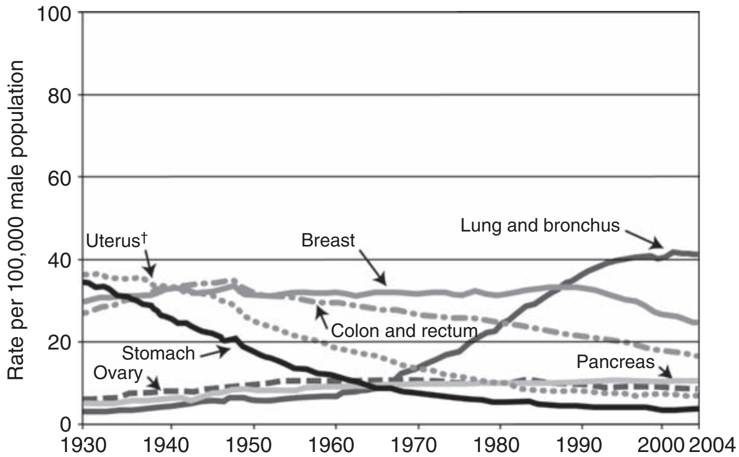

FIGURE 4.8

Age-adjusted cancer death rates, females* by site, United States, 1930–2004.
*Per 100,000, age-adjusted to the 2000 US standard population.
†Uterus cancer death rates are for uterine, cervix, and uterine corpus combined.

Note: Due to changes in ICD coding, numerator information has changed over time. Rates for cancer of the liver, lung, and bronchus, and colon and rectum are affected by these coding changes. *Source*: US Mortality Data 1960 to 2004, US Mortality Volumes 1930 to 1959, National Center for Health Statistic, Centers for Disease Control and Prevention, 2006. American Cancer Society Surveillance Research, 2008.

Cancer death rates for the major cancers for women and men (Figures 4.8 and 4.9) paint a different picture from the one presented by the Wingspread Conference. The graphs show an enormous increase in deaths from lung cancer; a decline in deaths from stomach, uterine, and breast cancers; and a roughly constant rate of death from other forms of cancer. These declines are not due solely to better medical treatment. Available incidence data show that, from 1975 to 2005, the incidence of all major cancers declined steadily, with the exception of breast and prostate cancer. In the case of prostate cancer, increased incidence is likely due to the introduction of regular screening, not necessarily higher occurrence.

The dominant pattern associated with cancer is the rapid increase in deaths from lung cancer up to the early 1990s, followed by an accelerating decline. Lung cancer is the cancer most closely correlated with personal choice, as opposed to those affected by factors over which we may not have control or by risks of which we are unaware. There is no evidence that modern technologies are causing increases in cancer.

The second major flaw in the Precautionary Principle rationale is that it considers "risky" actions in isolation. Every action that we take, from rising in the morning to constructing a nuclear power plant, presents risk and some level of danger. Unquestionably, building a nuclear power plant creates more risk to society than

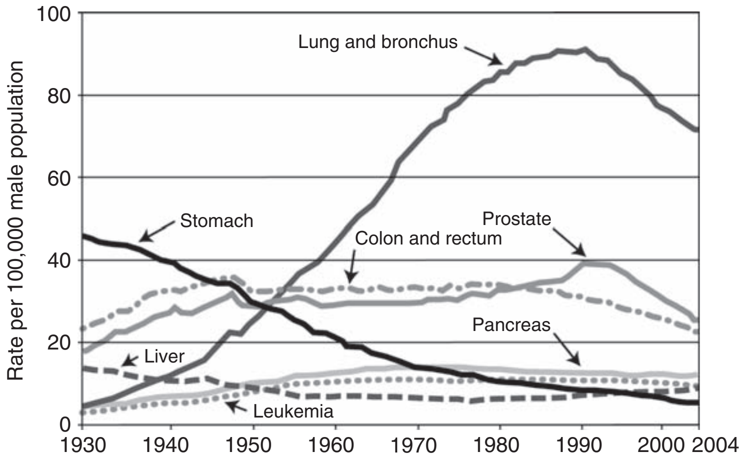

FIGURE 4.9

Age-adjusted cancer death rates, males* by site, United States, 1930–2004.
*Per 100,000, age-adjusted to the 2000 US standard population.

Note: Due to changes in ICD coding, numerator information has changed over time. Rates for cancer of the liver, lung, and bronchus, and colon and rectum are affected by these coding changes. *Source*: US Mortality Data 1960 to 2004, US Mortality Volumes 1930 to 1959, National Center for Health Statistic, Centers for Disease Control and Prevention, 2006. American Cancer Society Surveillance Research, 2008.

getting out of bed. But beginning a day carries more risk and danger on an ongoing basis to an individual than a nuclear power plant does.

Decisions are inherently flawed if decision makers do not consider the costs involved in choosing not to take an action. For example, a nuclear power plant carries distinct and serious risks, but not building one carries its own unique and distinct risks. The same quantity of electrical power generated by coal carries its own set of environmental consequences, ranging from greenhouse gas emissions to extensive land degradation.

In addition, declining to build any new electrical generation capacity creates its own set of problems. Lack of capacity may prevent people from moving to electrical energy for powering cars, thereby causing continuing high demand for petroleum-based fuels. Conversely, mandates for renewable energy may have unintended consequences. Foodstock-based energy can impact food supplies and affordability, cellulose-based energy can cause deforestation, and wind energy can decimate bird populations.

The message is that in order to identify the most sustainable policies, decision makers must examine the consequences of all potential courses of action, including no action in a particular arena. Multiple variables, many of which will be highly uncertain, are usually necessary to assess risk or danger. One cannot assume that "no action" is by default the most benign choice for the environment or long-term human health. Prudence itself, if it leads to excessive fear of action, can be a significant hindrance to effective decision making to achieve sustainable systems.

Our day-to-day individual risk management decisions demonstrate the reality that we prioritize in order to effectively use our resources to improve our lives and achieve acceptable risk management. For example, we may be willing to pay a premium for a car with antilock brakes and roll bars, which will clearly improve our driving risk. A converted Abrams tank (presumably with the weapons removed) would provide even greater safety, making us virtually immune to injury or death. However, the multimillion-dollar cost and the spinoff damage to the broader environment, as well as the likely risk of death to others on the road, make such a choice clearly ludicrous.

4.4 VALUES IN SUSTAINABILITY DECISION MAKING

The previous sections addressed the anomalies that arise in how we assess inputs to our decision-making process. Most of our problems with decision making seem to be hardwired into our brains. We all function with heuristics that provide rapid decision making shortcuts and cues to manage data overload. These heuristics, as discussed previously, often lead to illogical, if not absurd, choices. They would not exist, though, if they did not provide individuals, on average, with an incremental survival advantage.

Awareness of how we assess information in the decision-making process is only one component that we must deal with. Equally, if not more, important is our sense of what we want to accomplish with a particular set of decisions. We use many words to describe what guides us: principles, ethics, priorities, beliefs, and the like. But these value descriptors are themselves subject to forms of heuristics. They may be derived from a set of religious beliefs, political convictions, nationalistic or ethnic identities, or convictions regarding the relationship between the human species and the natural world.

Differing heuristics regarding the relationship between our species and the biological systems in which we exist and on which we depend create a sharp divide in views and approaches to resource sustainability. One side of the divide sees man as separate and distinct from the natural world, made in the image of a God that is the master and creator. Humans may have an ethical responsibility toward the Creator's creation, but that responsibility is an abstraction.

The other side of the divide sees man merely as another animal—remarkably adaptable and domineering, but an animal nevertheless. Those who have this view are typically comfortable with language that places natural systems on an equal if not exalted footing vis-à-vis humans. Both heuristics are influenced by an inescapable fact. A huge gulf lies between us and all other species because of our unique characteristics. We alone among all species can talk, write, and create staggeringly complex machines. We are likewise unique in that we have the power to engage in genocide, aggressively seek mind-altering drugs, and race to exterminate other species in the pursuit of short-term gain.

The challenge is to internalize into our heuristics a robust environmental ethic that acts on sustainability values over the darker traits of our nature. According to Jared Diamond, in the prologue to his book *The Third Chimpanzee* (2006):

> *The other black trait that now threatens our survival is our accelerating assault on our environment. This behavior too has its direct animal precursors. Animal populations that for one reason or another escaped control by predators and parasites have in some cases also escaped their own internal controls on their numbers, multiplied until they damaged their resource base, and occasionally eaten their way into extinction. Such risk applies with special force to humans because predation on us is now negligible, no habitat is beyond our influence, and our power to kill individual animals and destroy habitats is unprecedented.*

Diamond also discusses his premise regarding the potentially lethal relationship between humans and the environment with his book *Collapse: How Societies Choose to Fail or Succeed* (2005), in which he chronicled the collapse of societies through time due to the exhaustion of natural systems' carrying capacities. A common theme in the collapses was the apparent inability of social systems to adapt to the impact of their technological prowess on the natural systems upon which they depended. In nearly all cases the social power structures were unable to save their societies because they could not alter their pattern of interacting with the environment. Diamond muses:

> *What did the Easter Islander who cut down the last palm tree say while he was doing it? Like modern loggers, maybe he shouted "Jobs, not trees!" or "Technology will solve our problems; never fear, we'll find a substitute for wood" or "We don't have proof that there aren't palms somewhere else on Easter Island. We need to do more research. Your proposed ban on logging is premature and driven by fear-mongering!"*

Diamond's thoughts on why societies could make such disastrous decisions included lack of experience sufficient to anticipate the problem, reasoning by false analogies, failure to perceive a problem because of its slow augmentation (i.e., creeping normalcy), and conflicts of interest between people as well as between short-term and long-term perspectives.

Each of these problems has its origin in the conceptual models and psychological mind traps discussed earlier in this chapter, as well as in the heuristics we use for establishing our values. We must first be willing and able to perceive a stress on the environment and then internalize and accept responsibility. Accurate conceptualization of the problem, or at least a functional conceptualization, is only possible if we are aware of the factors that impede our thinking.

Decision making for creating sustainable outcomes will always be fraught with uncertainty and the potential for failure of a particular strategy. It cannot even begin, though, until our value heuristics are aligned with our need to maintain natural system robustness. The simplest starting point is the general principal of economics, as expressed by Landsburg (2007): "Things tend to work out best when people have to live with the consequences of their behavior, or, to put it another way, things tend to work out poorly when the consequences of our actions spill over onto other people."

This heuristic consists of screening our alternatives to ensure a mechanism to internalize costs to the ones who benefit. Such a framework for decision making is not value-free, but it transcends many of the barriers that exist between those with sharp ideological, religious, or political differences. Landsburg points out that as long as an individual feels all of the costs and benefits, he or she will tend to get the quantity right. Conversely, when some or all of the costs spill over to someone else, overindulging is not only likely but completely rational and unavoidable.

Altering a value system can be difficult. Allen Freeze in *The Environment Pendulum* (2000) observed that the way a person responds to trade-offs inherent in sustainability decisions is heavily value laden and affected by economic status. Concern over sustainability is a luxury to someone who is worried about finding something to eat tomorrow. The corner of the ring from which we emerge to the fight will govern the angle of our attack and our perspective. Freeze differentiated among libertarians who emphasize individual rights, those with egalitarian values who favor the least well-off in society, and those with utilitarian values for whom decisions are made to maximize the sum of individual utilities.

Regardless of perspective, a value heuristic of internalizing the cost to the beneficiary can provide a common starting point. Take for example the debate over how best to manage greenhouse gas emissions. The argument is polarized among those who deny there is a problem, those who acknowledge the problem but argue that any meaningful action would damage American competitiveness, and those who want to punish the culprits. Given the complexity of the issue, and the inaccessibility to the layperson of supporting research, it is not much of a challenge for each group of advocates to find the information needed to support its convictions. But surely there could be some common recognition, as a starting point, that there are spillover costs of our current energy regime that are not accurately allocated to its specific beneficiaries.

Some of the most serious and obvious spillover costs have nothing to do with direct environmental concerns. These include the cost of maintaining military forces to ensure safe access to oil, costs associated with the movement of large sums of our wealth to other countries, and the cost of the destabilization of critical regions of the world by the flow of unlimited petroleum dollars. In addition, the United States' high demand for oil results in inadvertent funding of hostile regimes in foreign countries as well as funding of ideologies hostile to U.S. interests. These are all distinct and very real costs that have only a tangential connection with environmental impacts such as greenhouse gas emissions.

Probably the spillover cost most difficult to comprehend is the transfer of costs from today to some future time. This is not just a transfer to a future generation but could easily be a transfer to a future that is as little as 10 years off. As stated by Hirsch and others (Hirsch et al., 2005):

> *Oil is the lifeblood of modern civilization. It fuels the vast majority of the world's mechanized transportation equipment—automobiles, trucks, airplanes, trains, ships, farm equipment, the military, etc. Oil is also the primary feedstock for many of the chemicals that are essential to modern life. This study deals with the upcoming physical shortage of world conventional oil—an event that has the potential to inflict disruptions and hardships on the economies of everycountry. … The earth's endowment of oil is finite and demand for oil continues to increase with time. Accordingly, geologists know that at some future date, conventional oil supply will no longer be capable of satisfying world demand. At that point world conventional oil production will have peaked and begin to decline. … A number of experts project that world production of conventional oil could occur in the relatively near future. … Such projections are fraught with uncertainties because of poor data, political and institutional self-interest, and other complicating factors. The bottom line is that no one knows with certainty when world oil production will reach a peak, but geologists have no doubt that it will happen.*

The important point is that there is currently a host of spillover costs that are unrelated to environmental concerns. Most of these spillover costs are being borne by general tax receipts by the federal government or are being offloaded to future years, which may not be far off. As stated earlier, without proper allocation of the true costs of a beneficial product or action, beneficiaries have a rational and reasonable incentive to overindulge. Eventually someone will pay, but the current system provides poor market signals to ensure that the actual beneficiary will pay appropriately. The simplest starting point for regulating greenhouse gases is to first concentrate on internalizing the true costs of energy, including the environmental damage that is currently offloaded onto the broader environment.

4.5 CONCLUSION

The discussion in this book links the way we think to the values we use to guide our thinking. In the following chapters, tools are presented for organizing our decision making so that we can avoid the common psychological traps and can more fully understand probabilistic consequences and the options for achieving desired outcomes.

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CHAPTER

Decision Consequence Analysis: A Paradigm for Decision Making

5

William L. Hall

5.1 INTRODUCTION

Decision analysis is a set of process and analytical tools that help people to think systematically and structurally about difficult decisions. The tools provide a means for structuring a decision problem by disaggregating the uncertainties, identifying participants' subjective beliefs about those uncertainties, and then constructing a quantitative decision/uncertainty model. Decision analysis encompasses computational techniques for probabilistically predicting positive and negative outcomes and calculating the utility of selected management approaches. It uses both factual and subjective information to evaluate the relative merits of alternative courses of action while offering insights into the impact of participants' judgments and beliefs. Decision analysis brings to the forefront the uncertainties inherent in the problem at hand and the opportunities for limiting their negative impact.

The approach taken in this text, termed *Decision Consequence Analysis* (DCA), focuses on the consequences of a decision. The DCA process allows these consequences to be assessed *a priori*, hopefully to improve the likelihood of achieving the desired outcome. Equally important, though, is the creation of a framework that allows feedback and decision adjustment as decision makers move into implementation. Documentation of the assumptions and uncertainties underlying a decision in a formal structure provides the tools for testing the assumptions and altering actions as assumptions are converted into experience.

The DCA procedure includes both a design framework and the analytical tools for mapping the interactions among objectives, alternatives, assumptions, uncertainties, probabilistic costs and benefits, and utility and risk profiles for the major decisions that must be made to control environmental liabilities. DCA analysis is all-inclusive in its consideration of physical, legal, political, and sociological constraints and expectations.

When applied, DCA can establish a trajectory of the actions that will be needed to achieve long-term objectives. It is also useful for specific short-term needs in environmental liability management projects, such as

DOI: 10.1016/B978-1-85617-797-9.00005-8

- Early identification of preferred pathways based on legal, physical, and fiscal constraints.
- Early elimination of financially impractical alternatives.
- Identification of cost escalation risks.
- Identification of decisions necessary to achieve fiscally responsible liability and business management outcomes.
- Communication among project stakeholders, including agency personnel, nongovernmental organizations (NGOs), other responsible parties, and potential adversaries.
- DCA is useful as well for the following mid- and long-term project needs:
  1. Developing benchmarks for decision effectiveness, expressed as a ratio of measurable environmental improvement over given periods of time to expenditures.
  2. Identifying the strategies, decisions, and tactics that can mitigate the most likely undesirable consequences, and prioritizing resource use accordingly.
  3. Optimizing strategies and tactics.
  4. Documenting liability reduction activities.

Water managers, planners, environmental officers, attorneys, and others charged with making key public policy or legal strategy decisions often face complexity and uncertainty, multiple and sometimes competing objectives, and differing perspectives among stakeholders. For these decision makers, perhaps no task is more difficult than balancing the many environmental, economic, technical, and legal objectives and implications to determine which strategy or alternative will best address all of them. At the same time, decision makers must account for the unknowns accompanying a changing regulatory environment or uncertain outcomes from the judicial process. DCA provides a number of methods, tools, and procedures that can help decision makers and others involved in decision making make these complex decisions.

5.2 BASIC ELEMENTS OF DCA

The DCA framework comprises several key elements, including the central decision, the trigger that necessitates the decision, objectives, alternatives, uncertainties, and performance metrics that measure the success or failure of outcomes. These elements can be assembled in different ways into a decision model. These key elements are discussed in the following subsections.

5.2.1 Decisions

A decision is a choice regarding an allocation of resources. This may be at the level of the individual, family, community, business, nation, or a group of nations. The resources we allocate may include time, accumulated financial capital, natural or labor resources, emotional energy, goodwill, and political capital. A decision is a commitment of resources. It may be revocable, but only through a new decision to alter the prior resource allocation. The decision maker is one who has authority over the resources being allocated. Presumably, he or she makes the decision in response to some trigger.

5.2.2 Triggers and Objectives

The need for a decision implies that there is something undesirable about the current state of nature. As an example, at the time of writing, Congress and several states are dealing with decisions regarding the implementation of renewable energy guidelines. This decision process is under way because aspects of energy policy at the beginning of the 21st century are perceived to be unsustainable, too costly, or dangerous to U.S. security.

Such conditions are triggers, that indicate that something about the current situation or environment is undesirable and needs to be altered. The awareness raised by these triggers in turn creates a decision space in which individuals or groups begin to consider changing the undesirable conditions. If the current situation is undesirable, the implication is that there is a preferable state of nature. This preferable state of nature is the objective—the target toward which the efforts to change the state of nature will be directed. It must be noted that this target toward which efforts are to be directed is often the most poorly defined or articulated component of the decision space. It is relatively easy to grasp that a current condition is undesirable or suboptimal. It is much more difficult to conceptualize, especially in a complex sustainability issue, the alternative state of nature that would be desirable.

5.2.3 Ends Objectives and Means Objectives

An ends objective is the ultimate state of nature being sought. A means objective, by contrast, is an intermediate step that in itself does not mitigate the triggers. For example, the creation of a federal policy on the definition of renewable energy is a means objective in that it can further the subsequent objective of increasing the use of renewable energy. Again, however, this objective is but another means to some goal. There is no benefit to the country, or to those engaged in the decision process, to increasing the use of energy, renewable or otherwise.

The assumption driving this means objective is that the use of renewable energy will increase energy independence. Even energy independence, in fact, is not the ends objective. Ultimately, the ends objective is improving the sustainability of the U.S. economy, which is highly energy intensive.

Working one's way through to the actual ends objective is vital to ensure that resource allocation is effectively directed toward a valid endpoint. A suggested approach for sustainability decision making is to continue asking the question "Why?" until a fundamental state of nature that satisfies the definition of sustainability is reached.

5.2.4 Performance Metrics

The decision maker should set performance metrics for his or her decisions. These provide a quantitative basis for measuring the specific degree to which an objective is being achieved. For example, the means objective of increasing renewable energy production and use may be coupled with the ends objectives of achieving sustainable forestry and economic growth in areas of chronic unemployment across a particular region, such as the southeastern United States. The performance metrics in this example could include the number of acres actively managed as diverse habitats, the total tons of wood available on a sustainable basis (without nutrient depletion) every year for energy production, and the net value of wood products by region.

5.2.5 Decision Models

Decision analysis is a structured way of thinking about how to mitigate the triggers leading to the need for a decision. It considers all of the common elements of decision making, including the decision(s) to be made, the alternatives associated with each one, the unique uncertainties associated with each alternative, and a measurement of the potential performance of each uncertainty against the objectives.

These elements are used to construct a decision model, which comprises logical and, as presented in this text, mathematical representations of the relationships within and among the decision elements. Decision models allow the decision maker to estimate the implications of each possible course of action so she can better understand the relationship between her actions and her objectives.

5.2.6 Alternatives and Uncertainties

For there to be a decision, there must be at least two alternatives, which are courses of action that might be taken. Each alternative has a unique set of uncertainties regarding its effectiveness and cost in achieving the objectives. Uncertainties are characteristics of the systems in which the decision is being made. The very act of choosing a course of action will change the environment that exists at the time of the decision. That is the whole point of making a decision: to change the state of the system environment. The uncertainties that must be addressed may be physical or social constraints; they fall into four general categories:

- Elements that are imperfectly defined
- Potential system responses that are imperfectly understood
- Uncontrollable conditions
- Simple imponderables

Different alternatives might subject the decision maker to different uncertainties, but in every case they combine with the uncertainties to produce the outcome, which is measured on the scale of the decision maker's performance metrics. The outcome in the decision model is always probabilistic. The likelihood of a particular outcome may approach such a high probability that it has the illusion of certainty. However, because of the universality of the four classes of uncertainty described in the previous paragraph, no decision is ever certain.

Because the outcome is the result not only of the chosen alternative but also of the uncertainties, it is itself an uncertainty. Take for example the previous comment on the intersection of objectives regarding renewable energy for improving forestry health and economics in the Southeast. Despite the best intentions, a chosen course of action could lead to large-scale conversion of diverse hardwood forests to pine plantations, perhaps fulfilling one objective at the unexpected cost of another.

5.2.7 Good Decision versus Good Outcome

The quality of the decision process and the quality of the outcome are not necessarily positively correlated. A bad decision may lead to a good outcome; conversely, a good decision may lead to a bad outcome. The quality of a decision must be evaluated on the basis of the decision maker's alternatives, information, values, and logic at the time the decision is made.

Nevertheless, the likelihood of an acceptable outcome can be universally enhanced by incorporating feedback mechanisms into the decision model so our future actions can adapt in light of the consequences of earlier decisions. We may not be able to predict outcomes with certainty, but we are capable of measuring results after the fact. When feasible, incremental decision milestones can help decision makers be responsive to outcomes.

5.2.8 Decision Structures

In a one-dimensional decision structure there is only one decision to be made, even though there might be many alternatives and the uncertainties themselves might be complex. An example of this structure is the decision faced by a landowner regarding management of his forest. His alternatives may be to grow the forest for 30 years and sell it for saw timber or grow it for 15 years and sell it for pulp wood. Although there are only two alternatives, the uncertainties can be highly complex. Issues of cash flow, timber or pulp price fluctuation, and likely disease or other forest damage all represent uncertainties involved in the landowner's decision.

The addition of simultaneous or sequential decisions creates a multi-dimensional decision structure. Decision makers in this situation need a strategy for addressing the several decisions at the same time. Each decision in the strategy will have different alternatives, and the decision maker must choose a coherent combination of them. The landowner in the previous example might simultaneously be trying to decide how much of his property he keeps in forest versus food crops and whether he joins a cooperative that allows him to spread his risk and benefit. His strategy must include consideration of the joint probabilities of his various combinations of decisions, as well as opportunities for mitigating the negative conditions that could impede the achievement of his objectives.

5.2.9 Portfolio Decision Problems

A portfolio decision problem is one in which various decisions are of a similar nature and the decision maker does not have sufficient resources for funding all combinations of alternatives. An example is a large multi-state property owner, such as a branch of the military. The decision maker is aware of many possible investments, but is unable to afford all of them. Specific combinations of investments may provide a higher probability of good results with less risk. In situations like this, the problem can be approached by prioritization. If one opportunity is prioritized higher than another, then, in the case of limited resources, the decision maker will choose to invest in the former rather than in the latter.

As an example, the U.S. Department of Defense has mandated that the bases operated by each of the armed services must meet certain sustainability goals, such as meeting a certain percentage of base energy needs with renewable energy sources. The Army, Navy, and Air Force each manage up to or over 100 bases across the country, with a total land surface in the millions of acres. A portfolio approach for the various sustainability goals allows each goal to be approached as a form of cap and trade. For example, a base in the Southwest may be particularly well suited for solar renewable energy. A portfolio decision analysis could help establish that one base is capable of meeting its own requirements as well as providing the renewable energy to offset requirements at another base that cannot generate power from renewable sources. This approach helps direct resources to the part of the portfolio where they can be used most efficiently.

Determining that it is preferable to fund project A rather than project B and project B rather than project C is a prioritization. Allocating funding for project A is a decision. A prioritization might be an intermediate step en route to a decision, and it might even be used as a tool to aid in a decision.

5.2.10 Options versus Alternatives

Some decisions offer the opportunity to adopt a particular type of alternative called an option. An option is an alternative that can be chosen in the future after further information has been gathered. All options are alternatives, but not all alternatives are options. Options are second-tier choices that consist of optimization of the first-tier decision. A strategy for implementing renewable energy projects across 100 Air Force bases is a selection of alternatives for combining projects and technologies across the portfolio. At each base, various options will be available for implementing the alternative.

Options have the potential of adding value to a decision situation. A wise decision maker is alert to that possibility and actively searches for valuable options. These second-tier choices, however, have the potential to complicate the decision framework. To avoid unnecessary complications, second-tier choices should not be of such a magnitude that in and of themselves they affect the validity of the overall strategy.

5.2.11 Risk and Utility

Risk is the possibility of an undesirable result. Decision makers have different attitudes toward risk, which can be described as their risk tolerance. A decision maker who is risk neutral is capable of accepting long-run odds—that is, the expected values over the course of multiple iterations of the same situation. For example, on average a flipped coin will be heads 50 percent of the time and tails 50 percent of the time, but that does not mean that it cannot be heads 10 times in a row. A focus on the short term reduces the capacity to accept the long-term odds, making it very difficult to be indifferent between the choice of receiving $1 for certain and the equal chance of receiving $0 or $2. Over the long term, with many repetitions of the same situation, the two alternatives yield the same result. However, for a single play of the game, the $1 certain gain is preferable.

As discussed in Chapter 4, we are hardwired to be risk averse. This means that we value alternatives at less than their expected values. To quantify a decision maker's valuation of alternatives, we can determine an alternative's certain equivalent (or certainty equivalent). This is the amount by which a decision maker would be indifferent to the choice between (1) having that monetary amount for certain and (2) having the alternative with its uncertain outcome. For example, a risk-averse decision maker might have a certain equivalent of $500,000 for an alternative with equal chances of yielding $0 and $2,000,000, even though the expected value for this alternative is $1,000,000.

An important aspect of structured decision analysis is that it provides a means to evaluate risk tolerance. Attitudes toward risk are heavily value laden and are affected by our socioeconomic setting. A gamble with equal chances of yielding $0 and $100,000 may be very risky for someone making minimum wage. Conversely, someone with millions in assets will not be as concerned about the stakes. For her these stakes are not large and may have a certain equivalent close to the expected value.

Decisions where risk aversion comes into play, particularly when there are multiple individuals involved, can be analyzed using a utility function. This is an algorithm for defining attitudes toward risk, developed by relating the decision maker's satisfaction with the outcome (or "utility" associated with the outcome) to the monetary value of the outcome itself. Utility functions can be indexed by their risk tolerance. The greater the decision maker's risk tolerance, the closer the certain equivalent of a gamble will be to its expected value.

The risk tolerance value is a mathematical quantity that describes the decision maker's attitude toward risk. It is a measure of the amount that the decision maker is *willing* to lose, not the maximum amount that he can *afford* to lose. As a general rule, decision makers with greater wealth have larger risk tolerances.

Note that monetary wealth can serve as an analog for other types of wealth as well as perceived wealth. The utility function or risk tolerance affects decision making through qualitative as well as quantitative reasoning. A decision maker with a perception that society has a significant reserve of a particular environmental asset may have a high risk tolerance for sacrificing part of that asset to achieve some other good. One with the opposite perception may respond much more conservatively. The task for a group of decision makers is to understand not only the differences in risk tolerance but the underlying experiences that create those differences.

5.2.12 Probability Distributions, Forecasts, and Uncertainty

Forecasts are predictions of the future. They are needed to assess the likely relationship between a combination of alternatives and the desired objectives. Forecasts attempt to predict the outcome, on all values of interest to the decision maker, associated with each alternative that might be chosen. They are expressed in quantitative terms according to the relevant performance metrics. For example, our landowner trying to decide between various land use options can use forecasts to quantify the elements of the decision framework. These may include time to maturity for his forest, pulp and saw timber demand at time of maturity, fertilizer and pest control costs, and his own cash flow needs. He can then predict the performance of a combination of land use choices.

When the quantities forecasted are uncertain, forecasters can describe their variability using a probability distribution, which provides a mathematical algorithm for expressing individual or collective knowledge regarding a particular variable. A probability distribution can be as simple as the coin toss described earlier. If the performance metric for a particular project is that it must be operational by a certain date, the state of knowledge may be that there is a 50 percent chance that it will be ready and a 50 percent chance that it won't.

Conversely, highly descriptive probability distributions can be developed using the Bayesian *a priori* knowledge discussed in Chapter 4. Once again, take a landowner deciding between land uses as an example. If his family business has been growing and harvesting trees for saw timber for generations and the family has maintained good records, an estimate of the most likely tonnage and the maximum and minimum range can be developed. In addition, he can adjust the distribution for the impact of modified cropping practices, changes in weather patterns from the past, or improved fertilizer or pest control.

After assigning probability distributions to each uncertainty, the uncertainty associated with the decision outcomes can be quantified. For example, our landowner can generate probability distributions for each of his alternatives. The outcome distributions provide information on both the expected value (or mean) and the uncertainty inherent in a particular combination of alternatives. The uncertainty is measured by the spread between the lower and higher percentiles, such as the 10th and 90th. These are possible low and high values, respectively, for a given uncertainty, set so that there is a 10 percent chance that the outcome will fall below the 10th percentile and a 10 percent chance that it will fall above the 90th. Similarly, the 50th percentile (or median) is the number that is equally likely to be above or below the eventual outcome. These distributions show the likelihood of achieving the desired objectives, measured using the relevant performance metrics.

Given these percentiles, the decision maker can test a decision's sensitivity to the uncertainties. She can assess how her choices might change depending on her risk tolerance in regard to particular objectives. This sort of analysis is particularly helpful when the decision is a collective one and involves individuals with different levels of risk tolerance and loss aversion. It also helps to achieve clarity of action. With clarity of action, decision makers understand why they, and others involved in the process, are making a particular decision. There is also transparency, for those within the decision environment as well as those affected by the decision, regarding how the decision was made. Knowledge of the critical uncertainties, and an understanding of how uncertainty was addressed, can help decision makers adjust their decisions in the future. This is the purpose of decision analysis.

5.2.13 Multi-Criteria or Trade-Offs

Economic viability is virtually always a central objective in decisions. The profit and loss associated with a decision represent the most robust performance metrics for whether an alternative or strategy is sustainable. If a course of action is unable to produce as much value as cost, it is not sustainable.

Other performance metrics are often necessary to fully define the performance space when the goal is sustainability. Many values that are intuitively recognized as essential to sustainable human and environmental systems cannot be accurately monetized. Examples are protection of clean water, maintenance of diverse ecosystems, and protection of species.

In such multi-criteria settings the decision maker will have to make trade-offs between values—judgments about how much can be sacrificed of one value in order to receive more of another. With our landowner, there may be trade-offs between the income streams generated from conversion to a pine plantation and the goal of protecting biological diversity.

5.3 THE DCA PROCESS

Although decision theory can involve complex problem structuring and probabilistic computations, the general process can be summarized as follows.

5.3.1 Baseline Physical Constraints

The first step in the DCA process is the compilation and evaluation of relevant data in a database that allows effective access to and analysis of it. If the relevant information has a spatial component, a geographical information system (GIS) is essential for readily examining the spatial relations of the data. For example, in an environmental remediation evaluation all data pertaining to a baseline understanding of the constraints (chemical, structural, physical, etc.) that will affect management of real or perceived risk pathways should be compiled and distributed among the stakeholders or decisions makers.

It is essential that decisions and uncertainties be assessed based on fact (data) rather than anecdote. Having command of the data through databases and GIS and the ability to respond factually to stakeholder conceptual models ensures that data dominates decision making. In addition, equitable distribution of the data to all decision makers is paramount for maintaining a democratic balance of power.

5.3.2 Problem Formulation

Problem formulation consists of defining the triggers that led to the immediate need for decisions. Problems must be articulated with precision to ensure that the correct problem is addressed and that unwarranted assumptions and prejudices are avoided.

5.3.3 Definition of Elements

The next step is to define the objectives, alternatives, and performance metrics relevant to the decision. Objectives must be clearly stated, concise, and measureable. Decision makers must then identify the potential courses of action and develop the appropriate performance metrics for assessing the success of the alternatives. Subsequent chapters detail the importance of value-focused versus alternative-focused decision making.

5.3.4 Decision/Uncertainty Mapping

Once the problem statement, objectives, performance metrics, and potential alternatives have been defined, the next step in the DCA process is to map the interaction of decisions and uncertainties. Each path on the decision tree has its own unique set of uncertainties. Each decision alternative affects the range of options available for future decisions.

The decision process consists of decide–learn–adjust–decide again. Detailing the linkage between current and future decisions, information collection decisions, and uncertainties reduces the potential for extensive activities to be performed that do not materially improve the quality of the results. Decision trees provide the logic to resolve each of the identified decisions or issues.

5.3.5 Consequence Analysis of the Primary Decision

The consequence analysis describes how well each primary decision alternative meets the objectives. Consequences may be described qualitatively or quantitatively utilizing the performance metrics.

5.3.6 Selection of Alternatives and Actions That Optimize the Achievement of Objectives

The final step in the DCA is the selection of a recommended course of action that optimizes the utility of expenditures. This recommended course of action provides a starting point for developing consensus among the various stakeholders. The DCA is the tool for testing the sensitivity of the conclusions against varying stakeholder opinions and views.

5.4 CONCLUSION

The DCA process as just described is applied in an iterative manner so the decision structure can remain intact even as the situation evolves. As information improves during the course of a project, uncertainties are resolved and new uncertainties arise. Strategies and tactics are adjusted accordingly to continually reflect the current state of knowledge and evolving understandings of preferred endpoints.

Various tools and procedures for implementing DCA will be discussed in subsequent chapters.

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CHAPTER

Decision Consequence Analysis: Conceptual Model Formulation

6

William L. Hall

6.1 DCA MODEL STRUCTURE

A decision is a choice of a course of action among competing alternatives. If we are considering alternative actions, in some way we are not satisfied with the current state of affairs and wish to alter it. Consider a person driving to work by her regular route. If the commute is proceeding as normal and is within acceptable expectations of traffic density, speed of travel, and so forth, she does not need to make a decision about the route. But if the way is impeded by a serious wreck, malfunctioning traffic signal, or downed tree, the need for a decision arises. The characteristics of the commute are altered. The driver was in the acceptable condition of expecting to reach work on time; now she is in a condition of anxiety and discomfort.

A decision setting has suddenly been thrust on our driver. As soon as a decision setting occurs, a decision context begins form. The elements of the decision context, shown in Figure 6.1, are built around a core concept: there is an unacceptable condition, or current state of nature, and a desired condition, or future state of nature. To achieve a transition between these two states, it is necessary to have a qualitative and/or quantitative understanding of each, the possible pathways between the two, and a way to map or measure the progression between them.

How do the elements of this decision context interact? The decision is initiated when we become aware of an unacceptable state of nature. The change in our driver's expected commute is the trigger that induced her to consider alternatives. The trigger itself will thrust the driver into the need to engage in a *problem diagnostic*, to evaluate the nature of the problem—that is, what is causing the slowdown. The consideration of choices will depend on whether or not the problem is a tree across the road or a malfunctioning red light. A tree across the road may take hours to clear, whereas a blinking red light could cause only minutes of delay. The possible alternatives, and their respective benefit to the driver, will be evaluated in light of the characteristics identified in the problem diagnostic.

The other side of the decision setting is the target condition, the alternative state of nature, or the *objective(s)*, desired. There may be only one objective, and it may be as simple as reducing the delay. Other objectives may come in to play, though,

DOI: 10.1016/B978-1-85617-797-9.00006-X

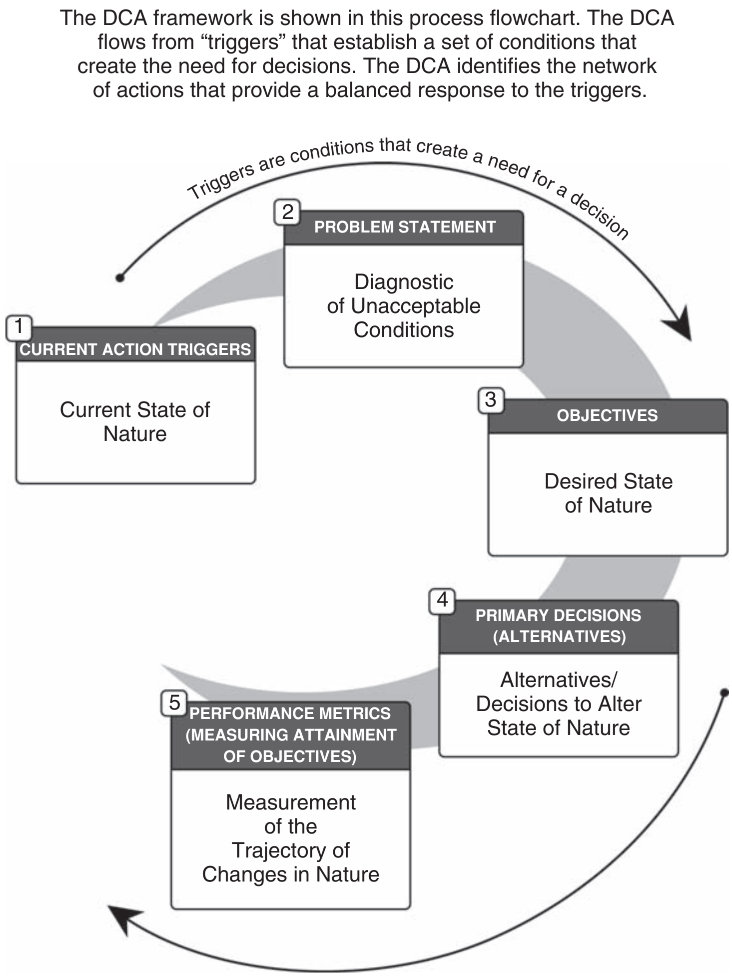

FIGURE 6.1

Elements of the decision context.

such as maintaining acceptable levels of risk to the car or driver or minimizing uncertainty. Imagine that our driver, following the problem diagnostic, has discovered that the blockage will likely cause no more than a 30-minute delay. The cause is a malfunctioning traffic light and a policeman has just arrived to begin directing traffic. Also imagine that our driver knows that an alternative route typically would reduce the delay to only 10 minutes. To complicate the situation, though, she also knows that the alternative route, if its traffic lights are also malfunctioning, is subject to much worse traffic jams. She does not know the status of the alternative route. However, using a Bayesian approach to consider probabilities, she taps into prior knowledge and realizes that if traffic lights are malfunctioning on her current route, they are likely malfunctioning on the alternative route. In this case an objective of minimizing uncertainty may take precedence over one of trying to minimize absolute travel time.

The two states of nature (current and desired) are subjective and depend on the exigencies of an individual or a group. Our driver has entered the decision setting because of her own needs. The road blockage creates a decision setting only because our driver is concerned about her travel time. If she is enjoying quiet time in a comfortable leather seat, listening to her favorite music on a top-of-the-line sound system, with no deadline, there is no trigger. The physical conditions remain, but they create no trigger.

The *alternatives* are the pathways for moving between the two states of nature. They represent the specific courses of action for mitigating the triggers that created the need for a decision. In contrast to the subjective triggers and objectives, the alternatives constitute concrete action. These actions will create or result in new physical settings that are themselves potentially unacceptable conditions.

For our driver, each route she may choose will have its own unique set of challenges, uncertainties, and imponderables. As she moves along any alternative route or stays put and waits out the blockage, her state of knowledge will continually increase. She will acquire data that was likely impossible to fully quantify at the outset of the trip, such as the number of commuters also trying the alternative route, the status of traffic signals, or the presence of traffic police. The decision context may also include several additional decision settings if additional route choices are encountered.

The *performance metrics* are the criteria used to compare alternatives, measure the degree of success or failure of a choice, and guide the modification of choices as the decision or decisions are implemented. Our hapless driver's performance metrics may be the likely time to work, the absolute minimum time to work, the maximum time to work, or the amount of gas that will be consumed. A performance metric, or a group of them, must be associated with each objective in order for it to be effectively considered. They may be quantitative or qualitative. It is desirable for metrics to be both measurable and subject to feedback measurement. If not, decision makers should try to develop metrics that can be addressed through Bayesian probabilistic reasoning. The most difficult metrics are heuristics that can only be partially tested against the unique realities of the situation at hand.

6.2 TRIGGERS AND PROBLEM DIAGNOSTICS

The first step in developing the decision context is to understand as precisely as possible the problem that needs to be solved and its underlying causes. The problem must be articulated with precision to ensure that the actual conditions creating the decision context are addressed and to avoid unwarranted assumptions and option-limiting prejudices.

6.2.1 General

An effective understanding of the actual problem is the most important, most overlooked, and most difficult component of establishing the decision context. Developing this understanding can be especially difficult when addressing the highly complex issues society faces in creating sustainable human and environmental systems. It is difficult to obtain consensus on first principles with issues such as water resource allocation among farmers, businesses, households, and the environment, or prioritization of transportation funds between new highways, high-occupancy lanes, or improvement of mass transit. Many decision makers are tempted to move immediately to alternatives and begin comparing them within narrow criteria rather than begin by exploring the actual underlying issue.

Individuals have different perspectives based on their training, background, and experience. An engineer may have a tendency to see a particular problem merely as a need to select an engineered solution to resolve a system bottleneck. An economist may perceive the same problem as instead one of determining if the system itself is the correct one. Perhaps the issue is not the bottleneck but instead the engineered system in which it is a component. An environmentalist, by contrast, may see the problem as the relationship of the particular engineered system to the natural systems in which it functions.

The challenge is reaching an accurate understanding of the underlying problem. One approach is to continue asking the question "Why?" until there is no further explanation. Take our driver. Her immediate observation is that the unacceptable state of nature is the blocked traffic. But why is the blocked traffic a problem for her? Is it because she will lose her job if she is late? And why might she lose her job? Is it because she is chronically late for inappropriate reasons and her supervisor has warned her that once more and the job is terminated? The problem, in this case, at its most basic level, is that she must have a plausible explanation for her supervisor.

A robust understanding of the problem changes both the objectives and the alternatives that may be useful for reaching them. Let's assume that our driver is chronically late to work and has been warned that one more incident will result in termination. The problem becomes more completely defined as being (1) the likelihood of being late and (2) the inability to communicate effectively to her supervisor that conditions beyond her control were at play. With this broader understanding of the problem, the objectives, and therefore the alternatives, are different. The primary objective may best be achieved by leaving the car for the moment to find another commuter who will lend her a cell phone. This alternative may provide a much higher probability of a successful outcome than frantically turning around and exploring highly uncertain alternative routes.

Debates surrounding public policy on large-scale systems such as transportation encounter the same difficulties in problem definition as described for our suffering commuter but at a much more complex level. An example is the debate in the early 2000s over Atlanta, Georgia's Northern Arc, a proposed 59-mile controlled-access highway. Originally with a price tag of $2.2 billion, the Northern Arc was proposed to run east–west to connect Interstate 75 northwest of Atlanta to Interstate 85 to the northeast. The highway met heavy opposition from neighborhoods along its path and became an issue in the gubernatorial election of 2002. The new governor, Sonny Perdue, after defeating the incumbent in the election, declared the highway "dead" (Hart, 2009).

In 2007, however, the Georgia Department of Transportation (DOT) officials reactivated the route, believing the project was too important to drop. State Transportation Board member David Doss claimed, "It's a pretty easy argument to be made that the east–west connector is the single most important transportation project in this state" (Hart, 2009). A new Northern Arc was included in the projects Georgia proposed under a pair of transportation tax proposals.

The public debate demonstrated significant inconsistencies in the understanding of the exact problem the road was addressing. In 2002, the DOT's official position was that the roadway was intended to divert traffic, mostly large trucks crossing the state, off Interstate 285, the loop road surrounding the city that is a chronic source of commuting nightmares for the Atlanta metropolitan region.

A 2002 *Atlanta Business Chronicle* survey of area leaders reflected the inconsistent understanding of the problem. The range of responses can be seen in the following survey excerpts:

- *Favored construction*—Reason: Allows east–west flow without clogging Ga. 400 and I-285. Saves time, saves gasoline = less pollution.
- *Opposed construction*—Reason: It damages efforts to address local problems, takes money out of current TIP/RTP (Transportation Improvement Program/ Regional Transportation Plan) projects, and leverages future money for many years.
- *Favored construction*—Reason: East–west traffic north of I-285 is a nightmare and will continue to get worse as this most favored area continues to be the favorite growth area in Atlanta. Much more needs to be done, but the Arc should be a major part of the fix to keep nonlocal cross-traffic from the east and west off the existing arteries.
- *Favored construction*—Reason: The Northern Arc will relieve traffic congestion on the I-285 Loop and provide access to the 400 corridor from I-85 and I-75, which allows residents along the 400 corridor easier access to their employment centers.
- *Opposed construction*—Reason: I oppose construction of the Northern Arc because east–west connectivity could be achieved at a lower cost, and with less disruption, by widening existing east–west roads. Also, if the Northern Arc were to be built according to Atlanta Regional Commission specifications, it would have access and exits in only three or four locations, so people could not readily use the new road for east–west traffic anyway. So why build it?

As reported by a local weekly paper in 2002, there were other completely different views of the purpose of the road. Gwinnett County Commission Chairman Wayne Hill saw the Arc as the foundation for a new city the size of Baltimore or Boston. Under Hill's pro-road regime, Gwinnett County had become the poster child for rampant, suburban sprawl, with the county's population jumping from 650,000 to 1 million between 1990 and 2000, an average increase in population of 5 percent per year. For Hill, the problem was keeping the population growing. An essential component of that, he believed, was keeping the automobile-centric world humming. "I don't think you're ever going to get people to rely less on cars," Hill said in 2002. "I had a gentleman in here this morning. He says, 'My car is my freedom.' So as long as it's like that, I don't think we ever will get people not to drive" (Hart, 2009).

Why was the road needed? Was it to take trucks off of the existing east–west loop, relieve congestion on local east–west roads north of the city, or create a development corridor so that the counties north of the city could continue to grow? None of three very distinct arguments in themselves got to the core of the problem to be solved. Why was it desirable to take trucks off of the existing loop road? Was it to relieve congestion or shorten travel time for commercial transport between northwest and northeast Georgia? And why was there a need to relieve congestion? Was it to encourage further economic development, save energy resources, or provide a better quality of life for residents?

The desired state of nature and associated alternatives depend on the definition of the unacceptable state of nature, or trigger. For County Commission Chairman Hill, the problem was a need to keep the population growing. For the commuter who had seen his commute time increase from 15 minutes to 45 minutes each way, however, the prospect of increased growth provided little comfort. Many different stakeholders have varying aims; the resident wants to keep taxes low and his current job secure, and to maintain his quality of life; the commercial trucker wants to move goods more quickly; the large property owner wants to sell the family farm at top dollar for development; the entrepreneur wants good conditions for starting new businesses. Each stakeholder defines the problem differently, and as a result has a different understanding of the state of nature that must be changed.

Stakeholders' different definitions of the problem also affect the performance metrics they use to evaluate alternatives. For Hill, the measure of success in the Northern Arc debate was reduced to a population growth rate of 5 percent a year. The assumption was that the growth rate itself was a demonstration of well-being. The office that Hill occupied on the second floor of the Gwinnett County administration building is a commute of about 45 miles of jam-packed traffic lights from downtown Atlanta. The complex is about a mile away from any business, restaurant, gas station, or home in Lawrenceville. Hill's situation jibed perfectly with a philosophy that growth and congestion are signs of progress and that there is no need to interact in a sustainable manner with environmental systems.

However, many other performance metrics could have led to very different valuations of alternatives, such as property taxes, commute time, access to open land, cost of living, and civic engagement at the community level. Many of these would have been better metrics than growth rate alone. Population density was already damaging quality of life in Gwinnett County—in areas near the Mall of Georgia, it could take over an hour to travel two miles by car (Hart, 2009). The growth rate could not increase at such a breakneck pace forever. At 5 percent Gwinnet would have a population of 4.5 million by 2030. By 2050 the population would reach 12 million, approaching that of some of the largest cities in the world. By 2100, the population would be a mind-numbing 150 million. At some point, growth has to stop.

In the shorter term, without accurate definition of the triggers that create part of the boundary of the decision context, investment of public funds and resources may create long-term unintended consequences. A Brookings Institution study reported that in Atlanta, "jobs, people, and prosperity have moved northwards and outwards, leaving a large arc of little or no population growth, economic decline, and an unusually high concentration of poverty on the south side of the city of Atlanta and its close-in southern suburbs" (Brookings Institution, 2000).

The Northern Arc issue is indicative of the failure of large-scale planning in a society that has the physical power and financial resources to irrevocably alter its environment. This failure starts at the definition of fundamental triggers for actions or decisions. It is, at its heart, a failure to diagnose the underlying problems that create the need for a decision. Regarding the Northern Arc, the competency and dedication of engineers and planners involved at the various levels of government and private advocacy groups do not need to be called into question. The failures derive from the absence of critical judgment regarding the definition of the problem.

Northern Arc decision makers analyzed the problem using deduction: analysis moving from general first principals, accepted as true, to specific applications. They started with a first principle, assuming that their first principal was the appropriate starting point for the decision context. But the first principle was assumed to be the need to create an additional vehicle corridor between two points. It was built on the idea that there were too many cars trying to occupy the same space and trying to consume a finite resource. As with population dynamics of any species, a solution is to find, provide, or conquer more habitat (i.e., highways) and to provide the growing population (cars) with access to the expanded habitat (highways). With this as the first principle, the planners and engineers had the general concept: the need for a habitat (corridor) to relieve the pressures of species (vehicle) population expansion. From this first principle, they could then optimize to the specific application.

But the diagnosis of a problem requires both deductive and inductive reasoning, and the application of effective diagnostic strategies. As just stated, deductive reasoning involves moving from general first principles that are accepted as true to specific applications. It starts with a true premise and moves to conclusions that are proven by their logical extension from an assumed true premise. In our Northern Arc story, the population of vehicles exceeded its habitat carrying capacity; therefore, more habitat had to be provided. Analysis in this type of reasoning can be focused on optimizing the specific.

But what if the premises are incomplete or there are valid contradictory premises? In the debate over the Northern Arc, years of dedicated evaluation of reams of data on a variety of aspects of the problem were available, but could not provide a comprehensive or unified definition of the problem. Evaluation of the evidence on both sides of the debate became a game of factoids and anecdote. Steven Vick expressed the problem well in *Degrees of Belief*, in his discussion of finding a solution to the failure of a dam. "A true conclusion could never be deductively reached because the premises could not be established as true. With this, the investigation hit a brick wall and a kind of paralysis ensued" (Vick, 2002).

In this case, the likelihood of the premise being true becomes probabilistic. With the Northern Arc example this could take several forms. Perhaps the lack of habitat was not the problem; instead, the population (of vehicles) itself was the problem. A competing first principle could be that the species itself (vehicles) was a problem or even an exotic invasive. The existence of excessive habitat and the creation of corridors for the species to colonize new habitats was the problem trigger, not a lack of new habitat (roads) and habitat corridors (controlled-access divided highways).

Resolving contradictory first principles, or challenging existing assumptions of first principles, is a vital component to achieving sustainability. In this setting, judgment is needed to utilize inductive reasoning that goes from the specific to the general. Deduction and induction operate on information differently. Deduction works from the general principle to produce proof of the need for a particular course of action. Induction, by contrast, operates on information regarding the specific to produce knowledge about the general.

6.2.2 Diagnostic Strategies

To define the decision context, inductive reasoning is essential if the correct objectives, alternatives, and performance metrics are to be identified. Rasmussen (1993) provided a framework for diagnostic strategies in which all diagnostic procedures have certain elements in common. The key features or events must be isolated and understood. These key events are the abnormalities and anomalies. In our Northern Arc example, the abnormalities include not only the disruption of functioning individual and commercial transportation systems but also the development patterns that produced undesirable feedback mechanisms, poor distribution of economic opportunity, and deterioration of air and water quality, open space, and habitats (of the native species, not of the vehicles).

Diagnosis involves finding the linkage between effect and cause, working both ways, sometimes simultaneously, and often alternating back and forth. When these links can be identified, causal narratives can be created that characterize the problem and the triggers as well as provide information on problem linkages. The linkages can be temporal or spatial proximity of occurrences, correlations between events, or the tendency for outcomes to appear under similar circumstances. This information is crucial to assessing alternatives.

Rasmussen (1993) identified three strategies for integrating the elements of a problem into a particular diagnostic, which depend on the perspective of the analyst and the direction of the inductive inference:

- **Variationist** strategy: from the intended condition to the actual case
- **Empiricist** strategy: from the expected condition to the actual case
- **Generalist** strategy: from the actual case to a larger generality

As described by Vick (2002), regardless of strategy, diagnosis can be applied in two different settings. One is a failure analysis, conducted after the fact to identify problem causation. The other is a risk assessment, conducted prior to the fact to identify mechanisms for potential failure. The first is a postmortem to learn what did happen; the second, a preventive, to predict what may happen. The two perspectives can often be at work simultaneously as one is attempting to isolate the triggers of a decision setting and diagnose the critical elements of the problem. The use and applicability of these strategies can be understood by looking at them from the perspective of particular problems and those who may be involved.

Variationist

The variationist strategy uses inferences that can be derived from the variation between a system's intended behavior and its actual measured behavior. It is deductive, as it derives from principles embedded in the intended or designed system functions. Consider the Northern Arc. The highway as proposed in 2002 was to be limited to only five interchanges. This component of the design was intended to limit access to reduce uncontrolled growth along the corridor. The limiting of growth was necessary, as the highway was designed to encourage diversion of traffic from the existing 285 loop road around Atlanta. But if the traffic predictions proved wrong, this goal would not be achieved and the problem that the road was to solve would reappear in a different place.

For the traffic predictions to be correct, extensive cooperation and restraints would be necessary from entities beyond the control of the Georgia Department of Transportation. As discussed earlier, based on the stated position of local politicians, there was likely to be significant variation from the intended design. Commissioner Hill saw the Arc as the foundation for a new city the size of Baltimore or Boston. Therefore, the problem diagnostics had to consider the realistic variations from the intended design. Boston proper has over 600,000 people; greater Boston, over 4.4 million. At least one stakeholder, with significant potential to alter the intended design constraints, had a much different definition of the problem than what served as justification for selection of an alternative.

Empiricist

The empiricist strategy also adopts a normal-to-abnormal approach to diagnosing a problem. The difference is that the problem is examined in the context of some expectation of system performance developed from prior cases. The decision maker makes an inductive inference about how the system will actually work based on how other, similar systems have performed under similar settings. By identifying a general case, inferences about the actual case are derived by matching it to patterns of behavior associated with various influences or causes associated with both settings. The patterns provide templates for correlating matching causes.

An example is the experience with overloading of the existing loop road around Atlanta (I-285). By 1978, within nine years of its completion in 1969, I-285 was in need of major upgrades. Atlanta was growing faster than anyone had expected and the entire freeway system was deemed obsolete. Route I-285 was the first project in the massive $1.3 billion “Freeing the Freeways” campaign. Its northern portion was widened to 8 lanes first (upgraded to 10 lanes in 1996). Despite these expenditures, the road remained a traffic nightmare, in part leading to the proposals to spend in excess of $2 billion for the Northern Arc.

An empiricist approach to the Northern Arc problem would involve identifying patterns in what went wrong in the previous planning and how those patterns might repeat themselves. The problem triggers that necessitated the original loop road, the upgrades in the 1980s, and the proposal for the Northern Arc have similarities. A problem diagnostic using the empiricist strategy would have provided a means to better understand that the problem was not merely one of establishing engineering criteria to build additional road capacity. Approaching the decision process with this diagnostic strategy would have increased the likelihood that expectations of many of the stakeholders would be met.

Generalist

The final diagnostic strategy reverses the direction of inference, going from the diagnosis of system failure in a particular case to generalizations about the failure's wider implications. Its simplest expression is learning from failure. Through the strategy's specific-to-general character, experience or empirical knowledge becomes incorporated in practice, engineering standards, or policies.

6.2.3 Summary

The decision context should be anchored by a thoroughly understood definition of the problem. This consists of identifying the triggers creating the need for a definition and a problem diagnostic of the problem itself. The purpose of the problem diagnostic is to ensure that there is an accurate definition of the triggers and that the alternatives will be capable of addressing the conditions that are creating an unacceptable state of nature.

6.3 DEFINING OBJECTIVES

An objective is an expression of a desired condition or state of nature at the other end of the decision context from the problem triggers that initiated the need for a decision. Changing the state of nature from unacceptable to acceptable is the sole reason for a decision-making setting. The objectives should provide a clear expression of what condition, at the end of the process, would result in satisfied stakeholders.

6.3.1 General

The objectives themselves are intertwined with individual values, which in turn arise from each individual's understanding of his or her own financial needs and qualitative well-being, as well as responsibility and connectivity to the larger community, the natural world, and subsequent generations. Each consideration has an effect on our objectives and on the way they mesh with those of other stakeholders in a decision setting.

At the simplest level, there should be at least one objective that expresses the alternate state of nature envisioned to replace each trigger. In our Northern Arc example, a trigger, at least for commuters on the existing Atlanta loop road, was "excessive commute time." An alternate state of nature, or objective, would be an "acceptable commute time." This objective was actually expressed in many indirect ways, including

- To connect Interstate 75 northwest of Atlanta to Interstate 85 to the northeast.
- To provide an alternate route for truck traffic.
- To provide a corridor around which economic growth could continue.

Note the difference in the various ways of expressing the objective. "Creating an acceptable commute time" responded to the most obvious trigger: excessive traffic on the existing Atlanta loop road. However, a review of the literature regarding the Northern Arc uncovered no mention that the decision context was established to achieve an acceptable commute time. The trigger of the unacceptable commute time was well represented in discussions, but an expression of the alternate state of nature specific to this trigger was not to be found.

The problem was approached not from the basis of the core need but from an attempt to optimize what appeared to be an obvious solution, at least obvious to those with specific vested interests. The chain of reasoning was straightforward. The existing loop road was overloaded and creating commute times, or commute conditions, that had extended beyond the tolerance of a high percentage of commuters. Some of that traffic was associated with cars and trucks that were attempting to travel between the northeast and northwest corners of the state. Therefore, the objective was an alternate route so that traffic would disappear. Any vehicle diverted to the new highway would be one fewer on the existing highway. The new road would thus lessen traffic, providing more room for existing traffic.

This reasoning made sense for the vast majority of stakeholders affected by the unacceptable state of nature—commute times on I-285—as well as for the vast number of stakeholders who in the end would pay for the fix. However, it did not express the problem and objective accurately, and without an accurate expression of the objective, the likelihood that the proposed fix would lead the commuters to the promised land of acceptable commutes was greatly reduced.

The flaw in the reasoning was that the Arc road became the objective rather than an alternative. But there was a sizable constituency that viewed it as a development highway. And this development highway was likely to create its own traffic gridlock, thereby rendering the core objective of an acceptable commute unreachable.

The identification of objectives involves value-focused thinking. As described by Keeney (1992), such thinking entails starting at the best outcome and working to make it a reality. Those engaged in alternate-focused thinking, on the other hand, start with what is readily available and take the best of the lot. It was the latter thinking that planners involved with the Northern Arc were engaged in. What would be best for commuters on I-285, and the citizens of the state, may or may not have been construction of the Northern Arc. Its utility and long-term value, in relation to other solutions, in eliminating the trigger for the decision was and is unknown. Instead, the objective was almost immediately defined as building another road. The reasons for building the road evolved, grew, and morphed after the decision to build the road was made. Decision makers were considering not alternatives for improving the I-285 commute times but rather alternative design criteria and routes for the Northern Arc.

As further expressed by Keeney, a narrow focus on obvious alternatives is the easy way out of a decision problem:

> *This "solves" the problem, but a price is to be paid later when the consequences accrue. This is alternative-focused thinking. Value-focused thinking is more difficult and meant to be penetrating. There are mental costs and time associated with the exercise, but the benefits should well reward the effort as the consequences unfold.*

Effectively articulating objectives requires a high level of self-awareness as well as awareness of the short- and long-term pressures faced by stakeholders in a decision setting. Short- and long-term interests affect each stakeholder's interpretation of the objectives. Long-term interests may incorporate consideration of broader social well-being with concepts such as ethics, morality, and responsibility to others and the future. However, all stakeholders are also influenced by their own financial needs and quantitative well-being. These considerations translate into pressure to skew the definition of objectives to encourage activities with the highest likelihood of quantitative benefit. In the Northern Arc example, the roadway may or may not have solved the commute problem of the residents north of Atlanta. It may have been an excellent solution. But it equally may not have been and could in fact have exacerbated conditions and negatively impacted other vital environmental indicators across a much larger geographic area. In any case, the likelihood is 100 percent that it would have benefited certain stakeholder segments, who would have gained from some aspects of the project such as increased development and road building.

The task is complicated for decision makers who have the opportunity to engage in value-focused thinking to achieve long-term sustainable solutions.

The habit of alternative-focused thinking is deeply ingrained and much easier, especially in a setting with multiple stakeholders. However, as Keeney stated, selecting among alternatives is constrained thinking. Value-focused thinking removes as many constraints as possible and allows decision makers to invest mental effort in identifying and describing the state of nature that would be most satisfactory.

To improve decision making at the problem scale described for the Northern Arc, it is essential that the intellectual effort to define objectives be conducted within the context established by the problem diagnostic discussed in the previous section. Multiple alternate states of nature may be desirable in any decision setting. These range from those desirable to specific individuals in the short term to those with a long-term benefit to broader society. Few of us would be dismissive of a state of nature in which we were guaranteed to become millionaires, have a satisfying job, or own a successful business. These objectives may be completely appropriate for a decision setting involving the start-up of a new business or a change in employment or even a bet at the racetrack. But in decision settings directed toward obtaining sustainability, constrained thinking that limits the understanding of objectives to the immediate and the personal can lead to highly undesirable unintended consequences.

6.3.2 Identifying Objectives

It is necessary to make a distinction between ends objectives and means objectives. Ends objectives are statements of the state of nature that is the target of the decision-making activity. Means objectives are interim goals along the path to achieving the ends objectives. In our Northern Arc example, a possible ends objective could be the achievement of an acceptable commute infrastructure for north metropolitan Atlanta. By contrast, a means objective could be to provide alternative commute options between two high-volume points in the commute network.

Ferreting out the ends objective(s) requires becoming sequentially more specific and identifying the proper endpoint for the specific decision-making group. The process involves disaggregating statements of desired states of nature until a fundamental condition is uncovered. This process must be coupled with an understanding of the boundaries of the decision-making setting. As shown in Figure 6.2, the desired state of nature can continue to be disaggregated into more and more basic definitions of human or societal needs. At some point the desired conditions move beyond either the scope or the capability of a specific team to address them.

Choosing the boundary of the decision-making scope is in itself a component of the decision setting and is needed to completely define the decision context. It is governed by technical, social, and political considerations, nearly all of which are related to the power of the decision-making group to implement its decisions. The further the decision-making team can move the boundary of its decision context, the more likely that the decision-making process will be capable of constructing a robust and effective family of alternatives.

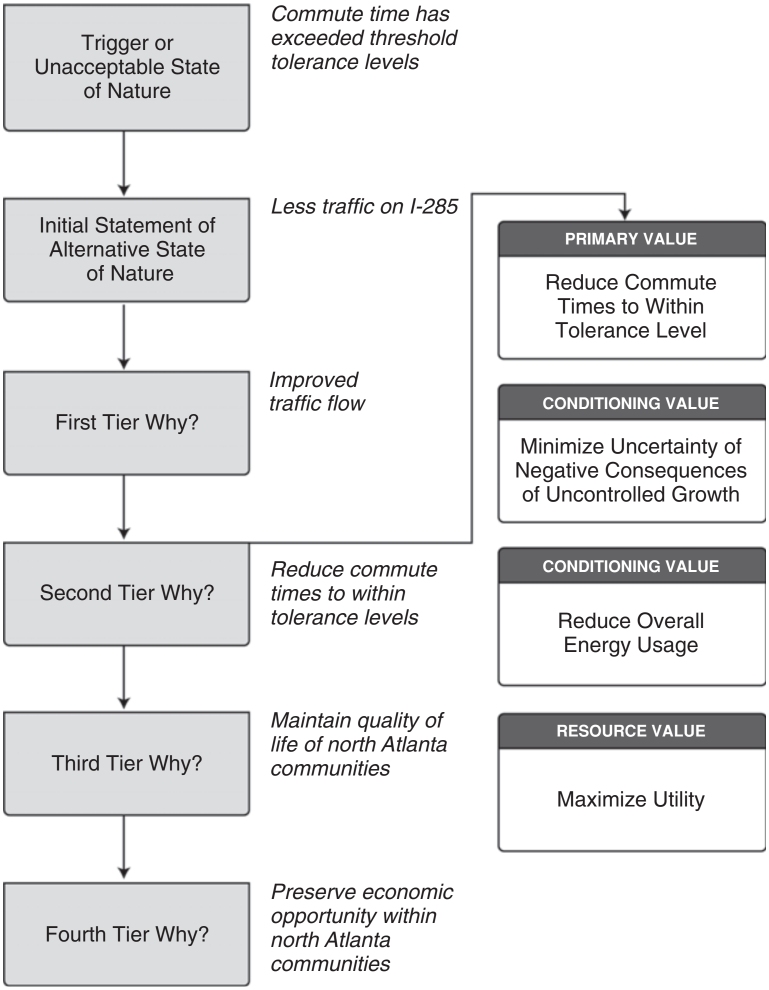

FIGURE 6.2

Defining objectives of values.

However, moving too far beyond a team's scope of capability can create a family of alternatives that overload the decision-making process. Ultimately, the objective of any decision-making process can be taken back to a first principle of achieving life, liberty, and the pursuit of happiness. Obviously, such a definition within a decision context would result in a minimum of constraints. Still, it would also move the process completely into the search for Utopia. The balance is in identifying the ends objective that allows creative and broad identification of alternatives while maintaining a practical connection to political, technical, and social realities.

An example of the process is shown in Figure 6.2, which provides an example of objectives definitions associated with the Northern Arc example. As can be seen, the initial definition of the ends objective is to reduce traffic on the existing loop road. Note that this is already several steps removed from the objective of constructing the Northern Arc. It is a logical and simple starting point, though, as it is an opposing condition to the project's trigger: excessive traffic on I-285. The search for the fundamental ends objective, however, can continue. Is the reduction of traffic on I-285 really the objective? Studies have repeatedly shown that increased capacity seldom if ever actually reduces traffic. By definition, the current traffic on I-285 represents the population willing to tolerate the existing commute times. Removing traffic by providing an alternative route may just as well result in the same level of congestion as exists under current conditions.

The next more basic description of the ends objective is the improvement of integrated commute times to within tolerable levels. This is a more fundamental response to the problem. The objective is to maximize the number of people who are able to get to and from work within their personal tolerance level. This objective opens up many more possible alternatives. A certain number of individuals on the current interstate system, even though they are not pleased with the commute time, decide to use the current option because of considerations of convenience, timing, the need to pick up their children at day care, and so forth. Conversely, a class of individuals places a high value on time and does not have a counterbalancing "cost" in the need for convenience. Alternative forms or means of transportation to and from work will be acceptable.

Additional, more basic objectives can be identified, as shown in Figure 6.2. But at some point, the increased flexibility in finding solutions offered by a more fundamental definition of objectives becomes counterproductive. In this example the decision setting is bound by transportation. Within that setting, the objective of reducing the total integrated commute time of the driving public in North Atlanta is within the realistic physical, social, and political boundaries of the problem trigger. Attempting to deal with what is perhaps a more fundamental objective, such as reorganizing development patterns in the northern metropolitan area, could lead to a family of alternatives that are excessively broad and virtually impossible to address on a practical scale. This does not mean that an awareness of such more fundamental objectives is unimportant or that they should be ignored. The knowledge of these objectives can be incorporated as a conditioning, nonquantitative consideration within the decision context.

6.3.3 Conditioning, Utility, and Means Objectives

As shown in Figure 6.2, the fundamental ends objective has means objectives consisting of conditioning and utility objectives. The conditioning objectives are those that may not be the primary concern but represent values that are intertwined with the decision setting. The example shown in Figure 6.2 indicates the conditioning objectives of effective land use and reduced fuel or energy use. Neither is directly related to the resolution of the commuter problem. If not considered with each of the potential alternatives, however, unintended consequences could leave the transportation system in worse shape after the alternative is implemented. After all, the trigger exists in part because of a lack of effective land use controls to control or reduce demand for transportation infrastructure.

The utility objective is typically part of any decision context. It is the measure of resources needed to implement an incremental improvement in the ends objective, and may also be applied to the conditioning objectives. Any decision involves a commitment of resources, which is a decision to improve or ameliorate an unacceptable condition; it is simultaneously a commitment not to invest in some other need. The utility objective provides the scale against which the marginal benefit of the expenditure can be judged against the other needs. Its form also provides a method to flush out the confusions that exist when alternatives are confused with objectives.

Comparison of alternatives against one another, as opposed to comparison of their ability to achieve the ends objectives, produces a cost–benefit setting. With a cost–benefit analysis, the selection becomes the least expensive in the family of alternatives, the assumption being that the alternatives are merely different representations of the objective.

As shown in Figure 6.3, a decision context may also have means objectives. The difference between a means objective and an ends objective is that each ends objective needs to have a specific performance metric. In addition, the means objectives are secondary statements of values that are desirable but not in and of themselves essential components of the decision context associated with the performance metrics. Performance metrics are discussed in more detail in Chapter 9.

6.4 DEFINING PERFORMANCE METRICS

A performance metric is a measurement of both the absolute state of nature achieved in terms of particular objectives and the trajectory of the changes between states of nature. The emphasis in the decision setting is on a probabilistic approach. A probabilistic assessment of the potential outcomes of a policy or major infrastructure campaign that may be conducted over decades captures the reality of decision making in a dynamic setting better than a simple measurement of the difference in expected outcomes. It provides a means to evaluate the actions actually taken against a range of possible outcomes.

The intent is to capture the true state of the “game” of sustainable decision making as faced by the players at the time decisions are made. The literature provides methods for developing the game conditions that must be considered in order to establish the realistic range of outcomes. John Harsanyi (1967) provided a foundational framework for analyzing policies in terms of their ability to achieve sustainability.

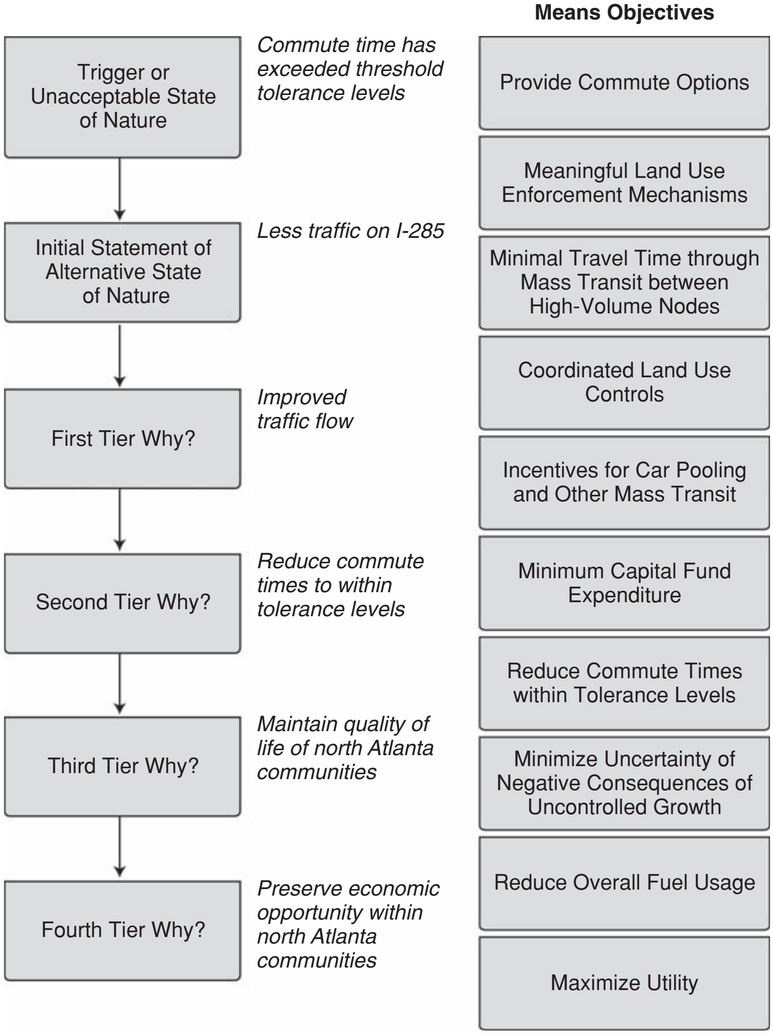

FIGURE 6.3

Means and objectives.

Harsanyi's theory involves the analysis of games with incomplete information. These are games in which the players are uncertain about important parameters of the game situation, such as the payoff functions and strategies available to various players. A game with incomplete information gives rise to "an infinite regress in reciprocal expectations on the part of the players." In other words, each decision (such as the selection of commute alternatives to relieve traffic congestion) is made in an environment of uncertainty. The players' responses (regulators, property owners, commuters, home purchasers, various governmental units, businesses considering relocation) are unknown, creating an infinite number of reactions. Decisions are recognized as being first order, second order, third order, and so forth. As soon as the first-order decision is selected, the combinations of constraints on subsequent orders of decision become infinite.

In Harsanyi's framework, expectations in a game with incomplete information are represented by multiple tiers of subjective probability distributions. The framework solves the complexity of an infinite combination of such subjective distributions by providing a theoretical basis for converting a game with incomplete information into one with complete but imperfect information. It involves converting each decision tier to chance moves that are assumed to occur before the players choose their strategies. The result is a probabilistic game in which chance moves each have a known probability distribution for the outcome.

The paper by Harsanyi further dealt with the problem that the attributes of the players in the game (e.g., state of knowledge, financial resources, technical expertise) are drawn at random from a population containing a mixture of individuals with a range of attributes.

Harsanyi's analysis of games with incomplete information uses the Bayesian approach. That is, a player assigns a subjective probability distribution to all variables unknown to him that is defined in terms of his own choice behavior. In contrast, an objective probability distribution is defined in terms of the long-run frequencies of the relevant events. It is convenient to regard the subjective probabilities a given player uses as being his personal estimates of the corresponding objective probabilities or frequencies he does not know or cannot fully quantify.

This framework applies to policy or large-scale land use decision settings because the players in the sustainability game are playing with incomplete (as well as imperfect) information. The imperfect information includes the physical and technical constraints, as well as the constraints and utility functions of the other players such as regulators, the business community, and governmental entities. In addition, the players have a time component. There are different sets of players 5, 25, and 50 years in the future, and each will face different physical, monetary, and sociopolitical constraints.

Each decision represents a random event that carries a probability distribution of outcomes. A player's choice of pathways is affected by her own subjective probability distribution. The distribution of a player's pathway choice will be affected by the state of her knowledge and the state of her expectations at various time intervals. This can be captured through distributions of the expected outcomes, financial and otherwise, associated with the objectives, as well as the variance around the expected outcomes.

The described approach replaces one in which outcomes are estimated deterministically and the deterministic outcomes are compared against fixed assumptions. Many attempts to craft sustainable policies fail because the appropriateness of a specific action is treated as if it were an independent decision made with perfect and complete information. Such an approach has no factual or theoretical basis. The conditions that must be postulated to justify such an approach simply do not exist.

The construction of analytical models to apply the probabilistic analysis of outcomes is dealt with in more detail in Chapters 7 and 8.

6.5 IDENTIFICATION OF DECISION AND ALTERNATIVES

Decisions are linked to alternatives. The quality of a decision process can be no better than the quality of the alternatives brought into the analysis. When a set of options is considered, a specific option may be selected as the superior one out of the set, but a more fundamental and important question is whether or not the family of alternatives is sufficiently robust. The temptation is to intuitively jump to a narrow subset of possibilities and take an option selection approach. This may be unconscious because of the psychological traps discussed in Chapter 4 or quite conscious because of narrow interest. If the only tool you have is a hammer, everything looks like a nail. A road builder wants to lay pavement, a developer wants infrastructure for new development, a commuter wants all the other cars to go somewhere, anywhere, other than the road on which he is traveling, and the engineer wants to design what he knows how to design, be it a road, a rail line, or a bicycle path.

The identification of alternatives and associated decisions should follow the establishment of the decision context. The decision context defines the constraints and the criteria that should dictate potential actions. The decision process is most effective when alternatives and associated decisions arise from a thorough understanding of the problem at hand. This is especially true when dealing with large-scale issues of sustainability, particularly land use, energy, and transportation.

The challenge and necessity of avoiding an option selection approach in addressing complex resource, land use, and human and environmental systems problems cannot be overstated. If the decisions and alternatives that are to be chosen do not flow from a thorough understanding of the decision context, the likelihood that the option selected will give sustainable results becomes a matter of luck. The problem diagnostic step, followed by articulation of the objectives and how those objectives will be measured, should be the starting point for identifying alternatives and the associated decisions.

The Northern Arc issue is an example of the difference between options and alternatives. Virtually all the interested parties accepted as a given that the highway had a certain value in providing additional habitat for vehicles. Both supporters and opponents agreed to this, independent of whether the supporters believed the highway was a boon for increased population growth, development, jobs, or reduced commute times on the existing highway system. The problem solving devolved to choosing the best route, design configuration, and public relations campaign to achieve the highway's construction. It was a case of choosing between options focused on how to build the highway, hopefully at the least cost and hopefully with mitigation of environmental damage.

A more thorough problem diagnostic reveals that the highway was itself positioned fairly far down in the decision hierarchy or sequencing. Its position could not be addressed until the triggers were understood and the objectives defined. The very core of the issue was whether the problem was insufficient automobile habitat, insufficient job opportunity or insufficient infrastructure to maintain population growth. Review of the public dialogue at the time reveals that these fundamental considerations were never vetted at the policy level. The set of alternatives to be considered and the hierarchy in which they were considered would have been more robust if the selection of decisions had been built from the decision context step.

For an objective of relieving commute time for existing commuters, the first tier of alternatives would have addressed decreasing the number of vehicles at any one time on the existing highways. In addition to the Northern Arc alternative, alternatives such as mass transit, expanded HOV, time-of-day pricing, and vehicle-type toll pricing could have been considered for total cost, utility, and uncertainty. Within each of the alternatives, subsequent decisions and uncertainties would have arisen. With mass transit, for example, multiple alternatives existed, from greatly expanded carpooling with direct subsidies and incentives to light or heavy rail along existing highway corridors.

There may be multiple objectives, and these may be in opposition. This is important to keep in mind when developing alternatives. In the Northern Arc example, increased economic growth could very likely have been counterproductive to reducing the commute. But with both of these, economic development and commute time reduction, the alternatives were broader than building the Northern Arc itself.

The Northern Arc would likely not have achieved its most commonly stated objective. Most probably the commute times for existing commuters would not have improved. Prior highway expansions in metropolitan Atlanta area had universally failed to reduce traffic congestion, with the commute time actually increasing by 20 percent from 1990 to 2000 (Pisarski, 2006), despite the Georgia DOT's much heralded Freeing the Freeway expansion program in the 1980s. In addition, with counties in the path of the proposed road led by proponents of population growth in the millions, the most likely outcome of the highway would have been expansion of the problem through a continuation of sprawl with few options for eliminating either the existing or expanded inventory of vehicles from metropolitan-area roads.

There are few situations regarding sustainability decision making in which there is a single decision. In most situations, one decision sequentially leads to another. In addition, the types of decisions are often materially different. As shown in Figure 6.4, decisions and their associated alternatives can be broken down into three classes: information, fundamental, and future. Fundamental decisions address the alternatives expected to directly move the current state of nature toward the desired state of nature. Information decisions are based on the fundamental decisions and may be narrowed by assessment of the fundamental decisions' consequences. Future decisions are the result of the choices sequentially made to change the state of nature. The approach is decide–learn–decide–learn–decide–learn. The intent is to break the scale of decisions down sufficiently to allow dynamic evolution of the state of knowledge, the decision making, and the measurement of the effect on the objectives.

6.6 UNCERTAINTIES AND CONSEQUENCES

The possible results from the selection of a particular combination of alternatives are the consequences. Many different uncertainties are associated with any decision or combination of decisions. What we are interested in are uncertainties that are relevant to one or more objectives, whether ends or means. The determination of an uncertainty's relevance can be deterministic or intuitive, but in either case it requires the judgment of the decision makers to identify uncertainties that can affect the quality of the decisions. The tendency is to focus on uncertainties that we can measure as opposed to those that can completely derail our expectations. For the Northern Arc, much attention was given to the relatively simple uncertainty over the actual amount of existing truck traffic that might be diverted from the existing Atlanta loop road. The glaring uncertainty that would render those uncertainties irrelevant was the resulting population growth rate and attendant traffic growth rate that would be the direct consequence of the new highway. This issue was never seriously debated by planners and proponents in public discussions.

The larger the number of uncertain events, the more complicated the decision setting. Unique combinations of uncertainties are associated with each unique combination of decision alternatives. In addition, the sequencing and interaction of decisions and uncertainties must be understood in order to derive a course of action that is most likely to advance the state of nature toward the desired objectives with the maximum capacity to adjust along the way.

6.7 CONCLUSION

A conceptual model of the decision setting is the essential starting point for addressing the complex multidiscipline problems associated with our civilization's quest for sustainability. Although it is essential, it is also the most neglected component in public policy debates. Without it, the selection of courses of action is reduced to balancing competing demands through comparison of preconceived options.

The conceptual model has as its basic building block and starting point, a definition of two competing conditions—the current unacceptable condition and some desired condition. With a starting definition of these two, the intellectual effort can then define the decision context by engaging in a problem diagnostic. This

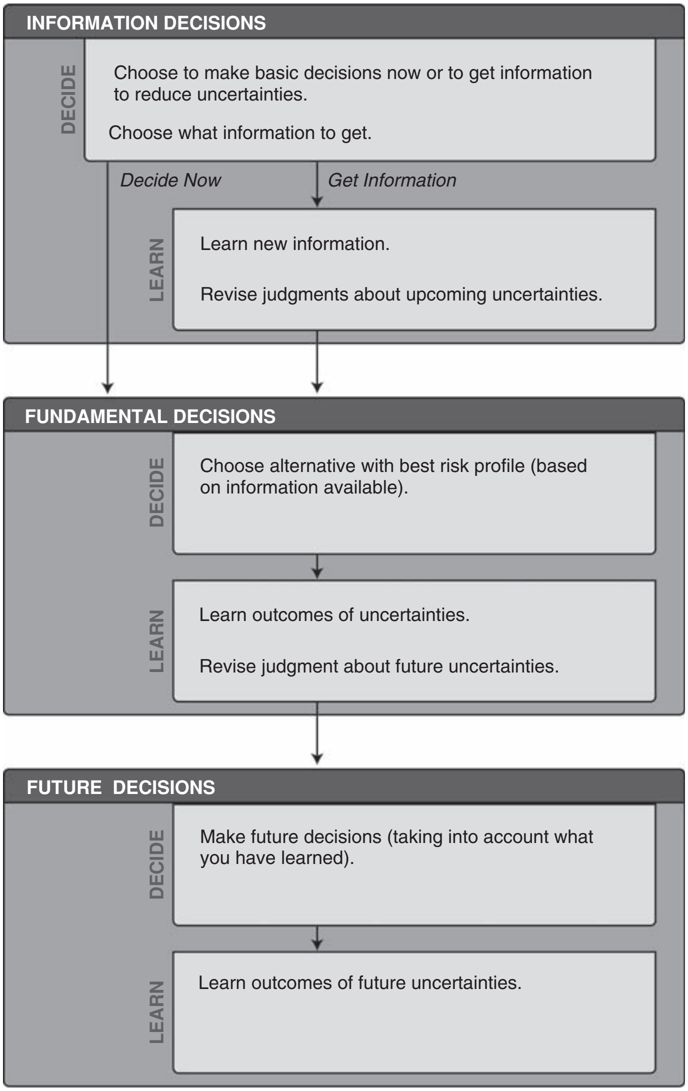

FIGURE 6.4

Tiered decisions.

diagnostic effort is comparable to a medical doctor using test data, experience, and deductive and inductive reasoning to isolate the possible root health problem.

Following the problem diagnostic, the decision team can move to the step of identifying decisions and alternatives. Further, a structure can be formed regarding the hierarchy and sequencing of decisions and how the alternatives may interrelate. Finally, performance metrics need to be developed for assessing how each combination of alternatives compares in achieving the desired objectives.

Chapter 7 presents a detailed example of decision model construction. Chapter 8 discusses multiobjective modeling. Analytical tools for generating the input values to a decision map, as well as creation of performance metrics for sustainability decision consequence models, are provided in Chapter 9.

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CHAPTER

Constructing a Decision Model

7

William L. Hall

7.1 INTRODUCTION

Chapter 6 provided guidance on identifying the elements of a decision problem and the thought processes needed to assemble a decision context. The second step of the process is to structure the elements of the decision situation into a logical framework. The two tools for achieving this are influence diagrams and decision trees. This chapter will provide an introduction to these tools and examples of their application. For a more thorough treatment of the subject, refer to Robert Clemen's *Making Hard Decisions* (1996) and David Skinner's *Introduction to Decision Analysis* (1996).

7.2 INFLUENCE DIAGRAMS

Influence diagrams are a graphical tool for mapping the interaction of the various elements of a decision setting. They usually represent decisions with rectangles; chance events or uncertainties with ovals or circles; calculated or fixed inputs and outputs with rounded rectangles, and outcomes or values with triangles (see Figure 7.1).

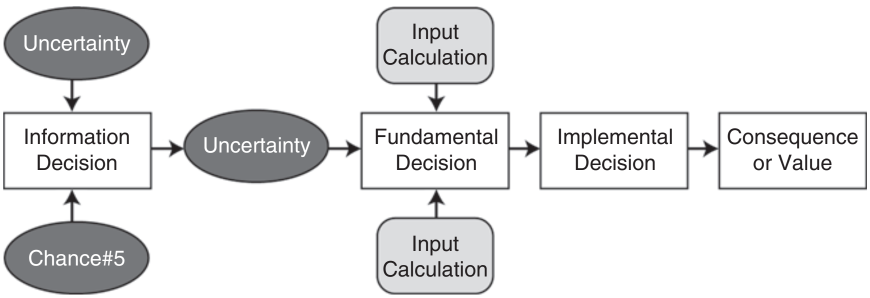

FIGURE 7.1

Influence diagrams.

DOI: 10.1016/B978-1-85617-797-9.00007-1

The four shapes are referred to as nodes. Decision and chance nodes are relatively straightforward. The rounded-rectangle node is more complex, as it represents a variety of elements of the decision setting. These may be measurable or probabilistically derived values that serve as inputs to a decision, characteristics of the chance nodes, or outcomes from a combination of decisions and chance inputs. The various nodes are assembled into a graph, with the interaction between them indicated with arrows or arcs. A node at the beginning of an arc is a predecessor; a node at the end is a successor.

Figure 7.2 is an influence diagram for a land use decision faced by a county zoning board for a request to rezone 10,000 acres from agriculture to mixed-use residential and light commercial development. The example nodes shown are greatly simplified for this discussion. It is assumed that the problem diagnostic has provided the decision makers with an appropriate decision context. The problem is not limited to short-term considerations of jobs produced or additional tax revenue. The problem diagnostic has generated sufficient baseline information for the zoning board to incorporate the impact of the development on a broader set of metrics, including long-term infrastructure issues of water supply and quality, transportation, social system sustainability indicators, and environmental sustainability indicators. In addition, the decision context has identified the three objectives as economic benefits, optimized societal indicators, and optimized environmental indicators.

Arcs establish the relationship between nodes. Generally, as shown in Figure 7.3, they represent either relevance or sequence, with the meaning indicated by the context of the arrow. Relevance means that the predecessor nodes have an impact on the value or assessment of subsequent nodes. Relevance connections mean that there is active influence between nodes. The direction of the arrow indicates the dominant dependent and independent variables. The predecessor node is the independent variable; the successor, the dependent variable. Often the interaction between relevant nodes is at least partially mutual or must be considered simultaneously. In such cases, an attempt should be made to break the influence down as a way to find the common variable affecting the nodes. Relevance arcs can originate from uncertainties, decisions, or calculations, and lead to other uncertainties, decision, and values.

Arrows into decision nodes represent sequencing. Everything prior to the decision has to be resolved before it is finalized. The decision is made on the basis of a course of action selected through the preceding nodes. The preceding nodes can be uncertainties, calculations, and/or decisions.

Note that when we say everything prior to the decision node is resolved, we do not mean that resolution has been achieved empirically or deterministically. For prior decision nodes, we means that a choice has been made that offers the greatest likelihood of achieving the targeted objectives given the range of subsequent decision alternatives. For uncertainty and calculation nodes, both of which are more than likely probabilistic, we mean that we have achieved an acceptable level of understanding of each of these inputs. For most inputs into a decision,

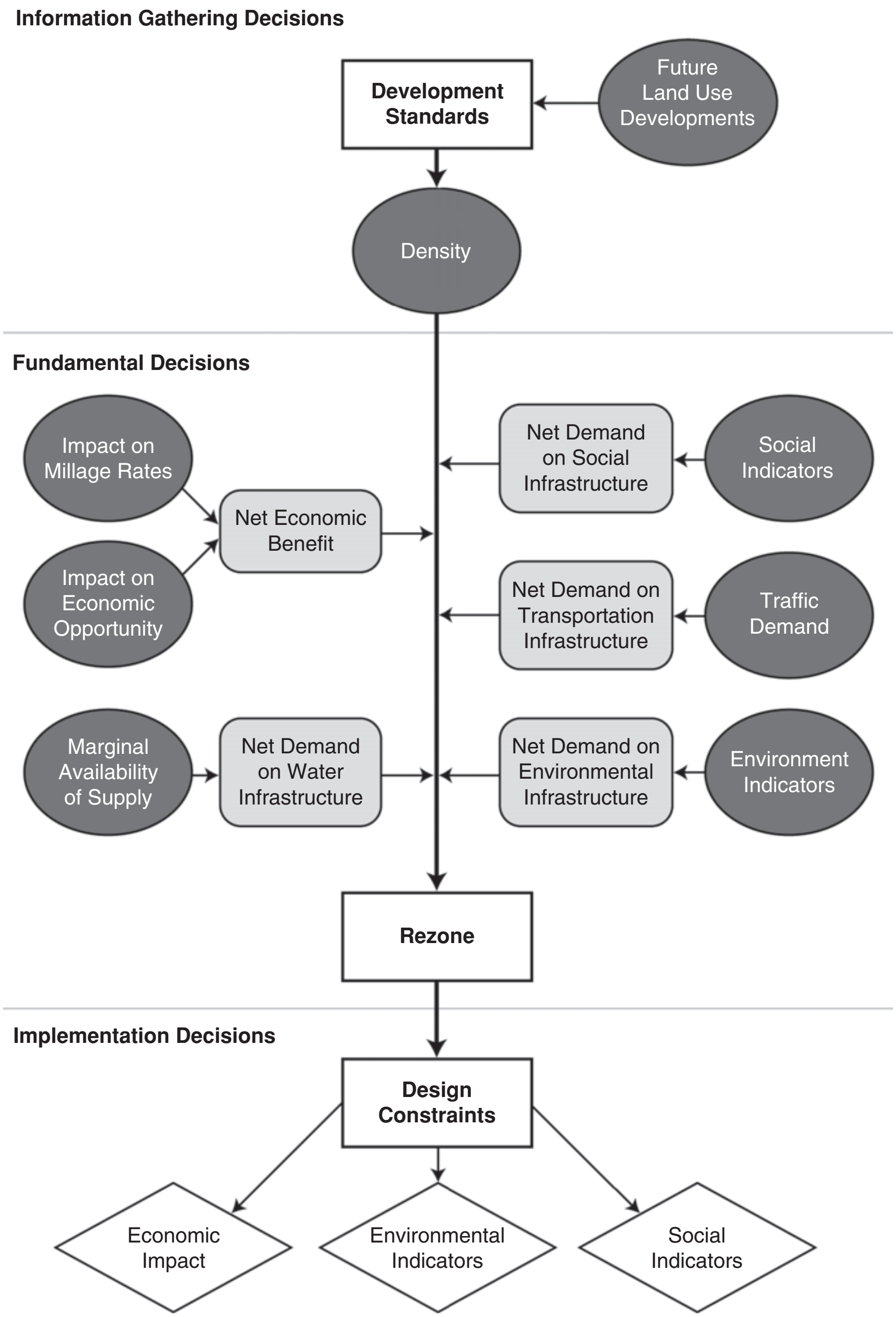

FIGURE 7.2

Decision influence diagram.

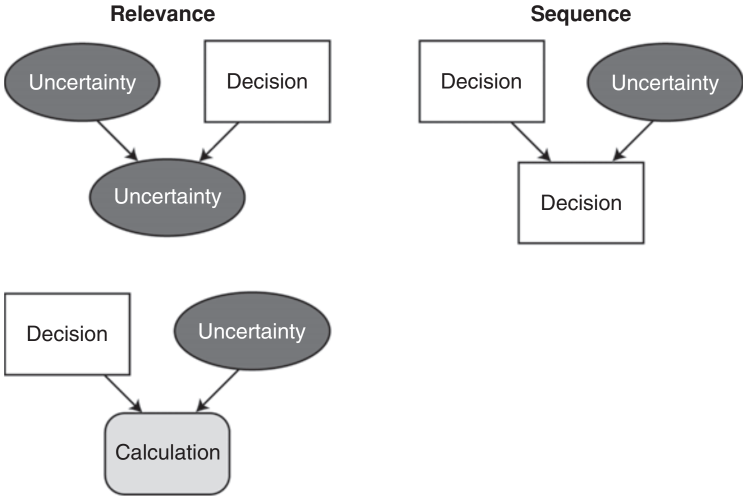

FIGURE 7.3

Relationships between relevance and sequence nodes.

certainty on the distribution of the variables' potential values is not possible, or at least not economically practical. However, the range of uncertainty can be reduced through prior information-gathering decisions. The presence and sequencing of such decisions are captured in the influence diagram.

A properly constructed influence diagram cannot have loops. Regardless of the location chosen as a starting point, no path leads back to that point. It is possible for values or outcomes to have a relevancy influence if they become part of the decision context for a sequential decision setting. For example, in our zoning decision example (Figure 7.2), the outcomes as measured against the objectives of environmental, economic, and social well-being might become uncertainties in subsequent decision making. These subsequent decision settings might include planning for the millage rate or policy decisions for other development activities, such as transportation or mass transit improvements, green space acquisition, regional biking and walking trails, and protection of water quality and watersheds.

The influence diagram shown in Figure 7.2 demonstrates the sequencing of decisions into information-gathering, fundamental, and implementation decisions. This sequencing allows the decision maker to identify the uncertainties of such magnitude that their resolution is necessary prior to advancing to the fundamental decisions. The implementation decisions are also a vital component of the decision setting, especially in the area of sustainability. A particular selection of alternatives will launch the decision makers on a path that is inevitably the result of a probabilistic assessment of the course of action that will give the greatest likelihood of achieving the desired objectives. The actual outcome, though, may be considerably different. Implementation decisions are based on the relevant uncertainties that are likely to influence the outcome, and on the ability to measure those variables during implementation and to respond to or adjust the course of action based on the outcome of those interim performance metrics.

Influence diagrams are the first step in the construction of a graphical model. As the problem becomes increasingly complicated or is dealt with at increasing scales, the usefulness of a comprehensive influence diagram diminishes. A point is reached where the complexity of the interactions or the sheer size of the diagram creates data overload. Frequently, the constraint is merely the size of the diagram and the inability to deal with the entire domain of influences in one drawing. In such a case, breaking the influence diagram into different tiers or scales of decisions can resolve the problem. The zoning decision, for example, can be dealt with as three distinct decision settings after the decision hierarchy of information, fundamental, and implementation decisions is defined.

There are some general misconceptions regarding influence diagrams. The most common is their interpretation as flow charts, with each node representing a distinct event and with the events sequenced more or less from left to right across the diagram. Instead, an influence diagram is a graphical representation of the decision setting. Constructed within the decision context as discussed in Chapter 6, it captures the influences, uncertainties, variables, inputs, and decisions necessary to change the state of nature from the unacceptable triggers to the desired state of nature or objectives. The values toward which the influence diagram is directed are the performance metrics with which the objectives are measured. The diagram should incorporate all elements thought to be relevant to the outcome, and should capture some idea of the range of uncertainty associated with those elements.

Another misconception involves the role of chance nodes when they are sequenced prior to a decision node. The question is whether or not the uncertainty must be resolved prior to making the successor decision. In fact, it must be resolved only in those situations in which the subsequent decision becomes contingent on where along the uncertainties distribution of outcomes the actual outcome will occur.

Take, for example, the uncertainty regarding alternative land uses in the rezoning situation. There may be a range of creative alternatives for the land that are attractive to both the county and the landowner. One example is its inclusion in land banks for carbon sequestration and wetland mitigation coupled with selective saw timbering and slag harvesting for cellulose renewable energy supply. If this alternative is found to be within the range of viable alternatives for optimizing the objectives, the uncertainty regarding its political and legal implementability will need to be determined prior to advancing to the next decision. If the attractive alternatives are insensitive to this particular uncertainty, the uncertainty's status does not govern the ability to move forward. At the time an influence diagram is developed, there may be many such uncertainties that can be irrelevant, but relevance cannot be determined until modeling has been conducted to reveal which uncertainties become critical and therefore sequential in the decision-making process.

7.3 DECISION TREES

Influence diagrams provide a useful snapshot of a decision setting, but primarily they assist in building the analytical framework, which is the decision tree. A decision tree for our rezoning problem is shown in Figure 7.4. As with the influence diagram, circles represent chance events or uncertainties and rectangles represent decisions. The branches emanating from a chance node represent the possible outcomes from uncertainties within the decision setting. Those emanating from decision nodes represent the choices available to the decision maker. The consequence is the calculated outcome at the end of each branch. Branches represent a specific combination of uncertainties and decisions.

Looking back at Figure 7.2, note the demand and return calculation values that are also inputs to the rezoning calculations. The inclusion of these in the decision tree is shown graphically in Figure 7.4 as the values on each branch of the density uncertainty. Based on the prior decision branch, the density in combination with the selected development standards creates a unique set of demands and returns that should be considered by the zoning board. Note also in the decision tree design that common branches have been collapsed to facilitate working with the tree.

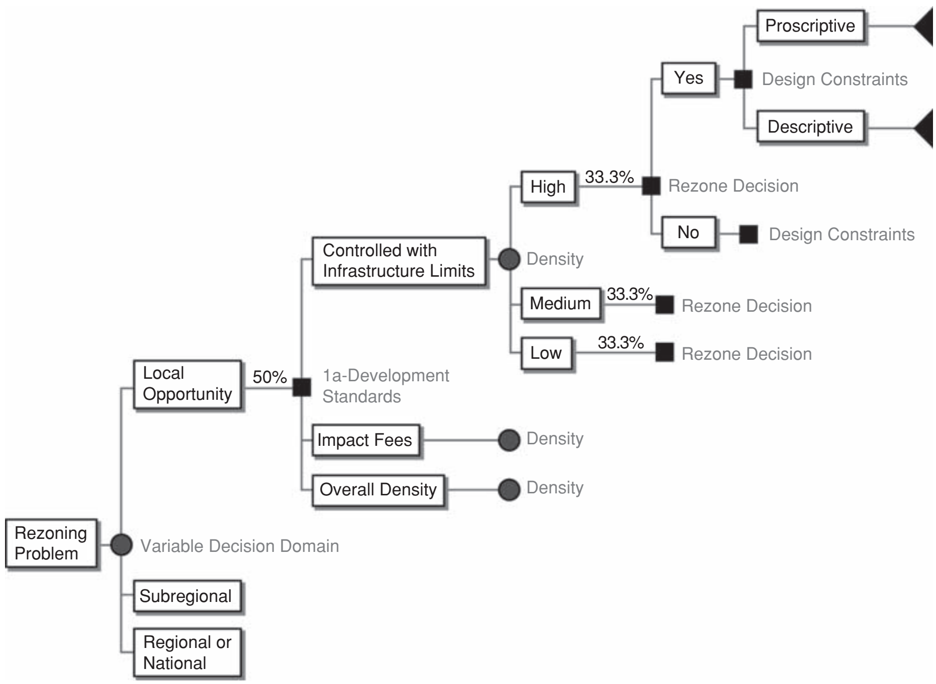

FIGURE 7.4

A decision tree.

Several guidelines must be kept in mind in the construction of decision trees. The first is that the branches emanating from a decision node must be such that only one branch can be chosen. In the rezoning example, for the preliminary information decision regarding development standards, the decision maker must select among various classes of standards. The example given is oversimplified for this discussion, but the choices shown range from infrastructure limits to overall population density limits. The infrastructure limits can include capacity of the development and its particular setting to allow for treatment and disposal of wastewater or the load capacity of area roads. The branches must represent a specific choice that becomes a defined constraint for subsequent nodes in the tree.

The second guideline, and one frequently misunderstood, is that each chance node must have branches that correspond to a set of mutually exclusive and collectively exhaustive outcomes. *Mutually exclusive* means that only one outcome can happen. For example, in the density chance node, three distinct outcomes have been indicated: high, medium, and low. Depending on the decision that comes out of the prior nodes, there will be different probabilities regarding the ultimate density of the development. Some choices will leave the ultimate density highly variable. If the development standard allows the parcel of land to handle its own sanitary water treatment, for instance, the range of densities can be significant.

A descriptive standard can result in a wide range of densities. Conversely, a proscriptive standard can result in a much narrower range. Note, however, that regardless of what type of standard is selected, the outcome is still an uncertainty. Decision makers have little to no control over many of the forcing functions that affect an issue such as density. These functions might include conditions in adjacent counties that influence the desirability of the particular development, the quality of the development, and the impact of future energy prices on where people wish to live.

The term *collectively exhaustive* means that no other possibilities exist and that one of the specified outcomes has to occur. Note that the outcomes can be assessed along a continuum as opposed to specific discrete outcomes that act as a step function. In the density example, three outcomes are hypothesized: high, medium, and low. As discussed in more detail in Chapter 8, the chance node can be entered as a distribution. Whether as a step function or as a distribution of outcomes, putting the two specifications together means that when the uncertainty is resolved, a distinct and measurable outcome results. This does not mean that the uncertainty has to be resolved prior to making decisions. If it is not resolved, the range of outcomes should be narrowed such that the successor decision is no longer sensitive to that specific uncertainty.

Specifying the likelihood of the different outcomes of a chance node requires the use of probabilities. The basic rules for probabilities are that (1) the probability of each branch must fall between 0 and 1.0 and (2) the cumulative probabilities of all of the chance node branches must add up to 1.0. Because the branches are mutually exclusive and exhaustive, it is not possible to have a cumulative probability of 110 or 90 percent. This can be thought of as the same chance setting that exists with flipping a coin. The coin must be either heads or tails; there is no other choice. If it is a fair coin, there is a 50/50 chance of either heads or tails. The coin may be altered, weighting it more heavily toward one or the other, but if the chance of falling heads becomes 60 percent, the chance of falling tails reduces to 40 percent.

Generally, the nodes along the decision tree represent time sequencing. The timing of events, such as the collection of information to resolve initial uncertainties and making prepatory, fundamental, or implementation decisions moves from left to right. The chronological order of our decision tree is

1. Resolving the uncertainty of alternative land uses.
2. Setting development standards.
3. Defining the range of resulting densities.
4. Developing cost and benefit inputs.
5. Deciding on zoning criteria.
6. Establishing design constraints and feedback mechanisms.

As with influence diagrams, the interaction of decision and uncertainty nodes in a decision tree is critical, and forces the decision maker to understand the interaction of events in the decision setting. A chance event before a decision means that the decision depends on refining the understanding of the uncertainty. Conversely, a decision preceding an uncertainty means that the characteristics of the uncertainty are contingent on the choice made. The sequence of decisions is mapped by their location from left to right on the tree. When no natural sequence exists, the order in which they appear is not critical. An example of this is the calculation inputs associated with the range of potential densities, which follows from the development standards. However, the various calculation inputs shown in Figure 7.2 do not fall into any particular order, although they do have to be defined before the zoning decision can be made.

Decision trees can address multiple objectives. The branches on uncertainty nodes may be and usually are different for the trees developed for the different objectives, but the branches for the decisions remain the same. A systematic way to examine multiple objectives is with a consequence or performance matrix as shown in Figure 7.5. Individual columns of the matrix represent one of the objectives. The assessment consists of populating the boxes with the performance metrics developed for each objective. In this case every combination of decisions will be evaluated against the three objectives of economic, social, and environmental well-being. Additional detail on developing performance metrics is provided in Chapter 9; a discussion of multiple-criteria decision making is provided in Chapter 8.

7.4 DECISION MODEL SPATIAL AND TEMPORAL SCALES

A decision tree should represent all potential paths through the decision setting. However, for the complexity of the decision settings that we are dealing with, identification of all pathways is impossible. The need is to identify the appropriate

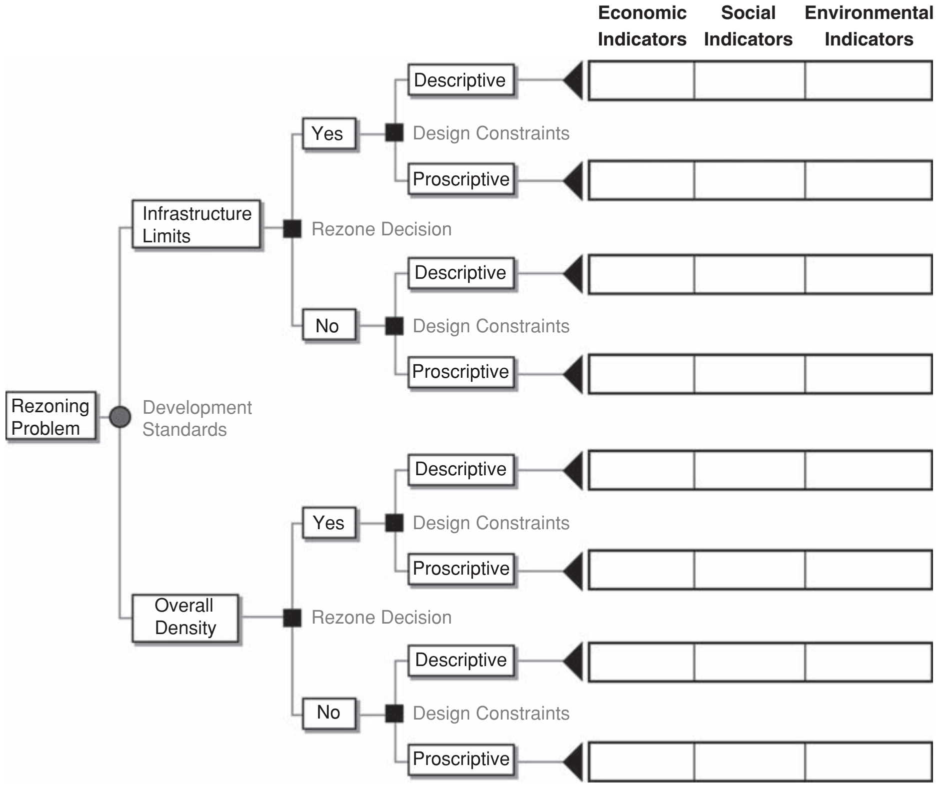

FIGURE 7.5

A systematic way to examine multiple objectives is with a consequence or performance matrix.

scale of the decision setting. Scale refers to the domain in time and space over which the decision is being assessed. In our zoning example, the scale could be just the 10,000 acres being considered, with a single objective such as maximizing the county tax base within the constraints of environmental regulations. Further, as is usual, the impact could be assessed over the limited 5-, 10-, or 30-year planning period typically employed in capital investment projects. At the opposite end of the scale, when we approach the decision from a sustainability perspective, assessment should consider a regional spatial extent, with multiple objectives and with unlimited time. Appropriately defining scope and scale is likely the single most important aspect of the proper design of a decision tree aimed at achieving sustainable land use.

The spatial scale, or at least the issues that might be associated with it, should first be identified in the problem diagnostic component when the decision context is defined. For the rezoning problem, five classes of analysis inputs were identified, as shown in Figure 7.6: economic benefits or costs, water infrastructure

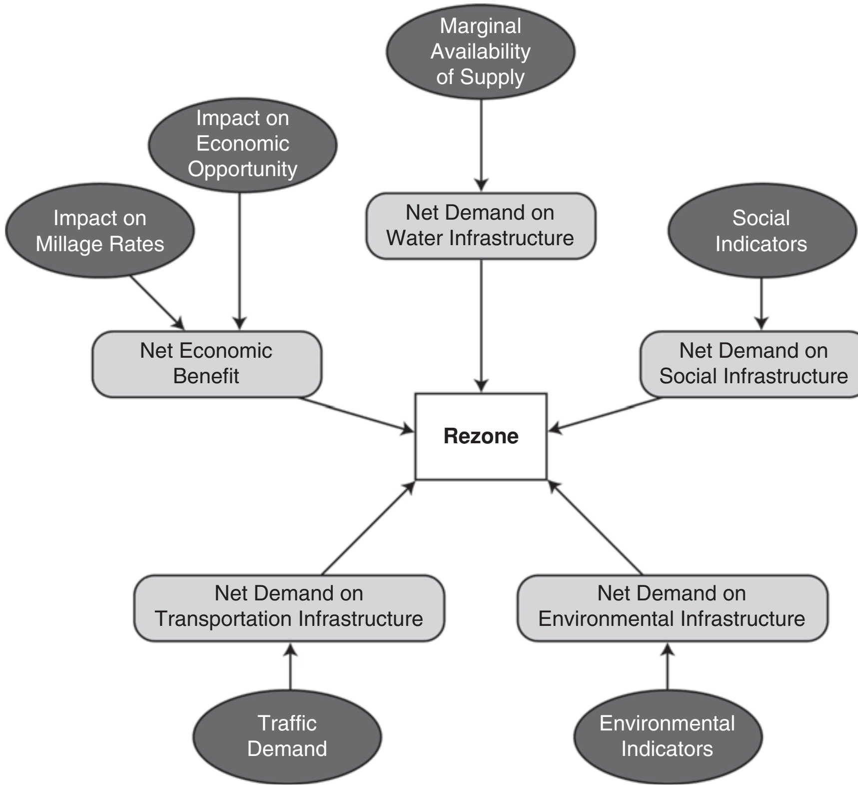

FIGURE 7.6

For the rezoning problem, five classes of analysis inputs were identified.

costs, transportation infrastructure costs, environmental indicators, and the costs of social infrastructure such as schools and services. Gathering the input data necessary to support analysis can grow more difficult as the spatial scale increases. The ability of decision makers to gather input to support decision making on large spatial scales is dependent on practical, political, and legal considerations.

Practical considerations relate to the complexity that a given group of decision makers can tackle given resource constraints. In our rezoning example, the 10,000 acres would be of a scale that could have some level of influence on environmental, economic, and societal indicators over a much larger region, and it could impact decision making ranging from regional transportation to water supply and treatment management among many states. At some point, though, expanding the scale of analysis becomes counterproductive as it leads to unmanageable complexity.

Political and legal considerations likewise affect the scale. Although it may lead to suboptimal results overall, choosing a smaller scale of analysis may be necessary so that decision making can effectively deal with uncertainty and achieve functional consensus. The decision setting can be constrained as much by too small a scale as by too large a scale. This can be demonstrated in our rezoning example with respect to threshold uncertainty. Included at the beginning of the decision tree, this uncertainty is the possible range of future land use opportunities that can be considered prior to setting development standards for the property.

Figure 7.7 is an example of the potential impact of this uncertainty on establishing a meaningful starting point for meeting the objectives. The default condition is that the zoning board is dealing with a straightforward decision of either denying the rezoning request or approving it, perhaps with some conditions. If the decision setting is limited to these options, the decision assessment in terms of sustainability indices is likely going to be a choice between two evils. Rezoning will guarantee the conversion of open space to more dense development. This will produce a variety of consequences, including a change in human population density, increased demand on infrastructure, and increased demand for government and social services. It may also have positive consequences, such as short- and long-term improvement in economic opportunity.

Nevertheless, the rezoning will provide the opportunity to exert some forward planning on the development and provide a level of certainty to the timing and nature of increased pressure on existing infrastructure. Without rezoning, depending

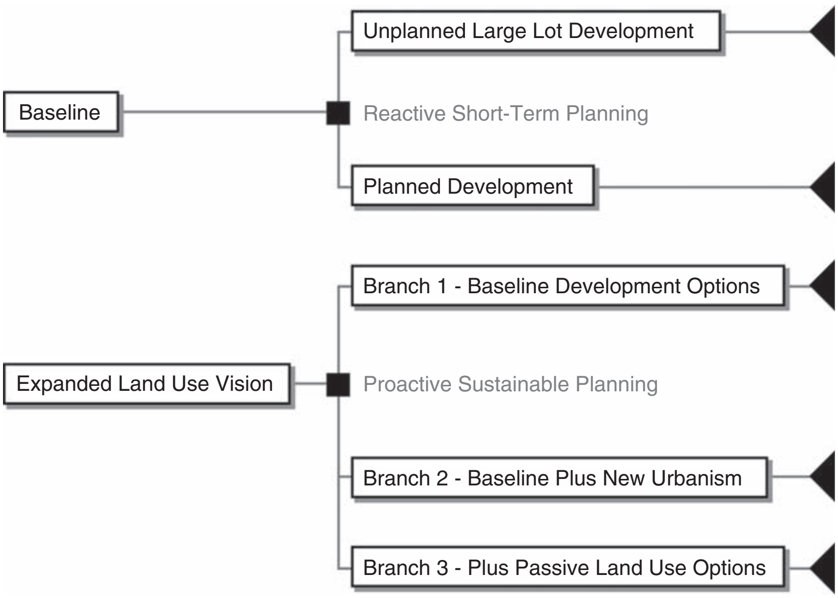

FIGURE 7.7

Example of the potential impact of this uncertainty on establishing a meaningful starting point for meeting the objectives.

on the nature of sprawl in the area in question, the property may be subject to conversion to more dense development anyway, but without the benefit of master planning. Instead of being developed as a unit, with some concentration of density and maintenance of appropriately connected green ways and contiguous habitat, the area may be developed piecemeal in lots just large enough to satisfy an agriculture zoning requirement, or sold off in smaller units for construction of conventional cul-de-sac communities. This type of development could potentially be much worse for all of the indices: economic, environmental, and social. There are several paradigms for expanding decision domains, some of which are discussed in the following sections.

7.4.1 New Urbanism

In this example, there might be dramatically improved conditions if the zoning board expanded its vision to a larger scale in space and time. The need is to expand the scale according to conditions beyond the boundary of what might be typically taken as the decision domain. The zoning board in our example has some influence within a well-defined political domain. This domain establishes the starting point for the decision domain. The board will very likely know what is happening at the edges of its political domain, but probably with a default assumption that such events are tangential to its mission.

However, not only may the events at the boundary of the political domain be susceptible to influence by the planning board, but also their incorporation may provide greatly improved results for all stakeholders. This is the uncertainty that is indicated by the first uncertainty node in the decision tree (Figure 7.4). Is the domain of the decision making to be limited to the immediate property? If so, the only viable alternative to rezoning is ad hoc, low-density development. If the domain is expanded, decision makers can consider actions to improve development patterns or, possibly, to obtain far more desirable results through passive land use options.

The second branch on the first uncertainty node in Figure 7.4 captures the possibilities introduced by expanded thinking on how human systems are organized. The concept is defined generally by the term **New Urbanism**, a design movement that arose in the United States in the early 1980s with the goal of reforming many aspects of real estate development and urban planning. New Urbanism neighborhoods are designed to contain a diverse range of housing and jobs and to be walkable so as to minimize dependence on cars. The underlying intent is to create human communities that more closely mimic the organizing principal of hamlet, village, town, and city that characterized societies prior to the 20th century. It is the reinvention of the old urbanism, commonly seen before the advent of the automobile age (Katz, 2004).

In its most sustainable fashion New Urbanism requires incorporating a property's development within a larger context. This larger view applies not only to the built infrastructure of roads and existing commercial and industrial work centers but also to the natural infrastructure. A good example of natural infrastructure is the availability of water supplies or treatment capacity as well as the availability of open green space. Further considerations can include the possible networks of local farm produce or other food sources. The natural infrastructure is finite and does not follow political boundaries. To incorporate consideration of these issues into the indices or performance metrics used to assess objectives requires determining if it is possible to coordinate cooperatively across the artificial boundaries established by political units.

The sustainability principle behind expanding the domain of decision making has been expressed by the Congress for the New Urbanism (CNU), founded by Peter Katz in 1993. The CNU is a loosely formed group of architects, builders, developers, landscape architects, engineers, planners, real estate professionals, and others who are committed to New Urbanist ideals. The group outlined their beliefs in an important document known as the *Charter of the New Urbanism* (2008), which reads as follows:

> *The Congress for the New Urbanism views disinvestment in central cities, the spread of placeless sprawl, increasing separation by race and income, environmental deterioration, loss of agricultural lands and wilderness, and the erosion of society's built heritage as one interrelated community-building challenge. … We stand for the restoration of existing urban centers and towns within coherent metropolitan regions, the reconfiguration of sprawling suburbs into communities of real neighborhoods and diverse districts, the conservation of natural environments, and the preservation of our built legacy.*

Defining the scope of the decision domain for the rezoning application discussed in this chapter, as well as for almost any decision setting dealing with sustainability, is a balancing act between the immediate pressures of short-term market forces and private property rights and the objectives of environmental, social, and economic balance. As recognized by the CNU in the following statement from a 2008 publication, improvement in the decision-making process without attempting to optimize the domain is likely to yield suboptimal results.

1. Metropolitan regions are finite places with geographic boundaries derived from topography, watersheds, coastlines, farmlands, regional parks, and river basins. The metropolis is made of multiple centers that are cities, towns, and villages, each with its own identifiable center and edges.

2. The metropolitan region is a fundamental economic unit of the contemporary world. Governmental cooperation, public policy, physical planning, and economic strategies must reflect this new reality.

3. The metropolis has a necessary and fragile relationship to its agrarian hinterland and natural landscapes. The relationship is environmental, economic, and cultural. Farmland and nature are as important to the metropolis as the garden is to the house.

4. Development patterns should not blur or eradicate the edges of the metropolis. Infill development within existing urban areas conserves environmental resources, economic investment, and social fabric, while reclaiming marginal and abandoned areas. Metropolitan regions should develop strategies to encourage such infill development over peripheral expansion.
5. Where appropriate, new development contiguous to urban boundaries should be organized as neighborhoods and districts, and be integrated with the existing urban pattern. Noncontiguous development should be organized as towns and villages with their own urban edges, and planned for a jobs/housing balance, not as bedroom suburbs.
6. The development and redevelopment of towns and cities should respect historical patterns, precedents, and boundaries.
7. Cities and towns should bring into proximity a broad spectrum of public and private uses to support a regional economy that benefits people of all incomes. Affordable housing should be distributed throughout the region to match job opportunities and to avoid concentrations of poverty.
8. The physical organization of the region should be supported by a framework of transportation alternatives. Transit, pedestrian, and bicycle systems should maximize access and mobility throughout the region while reducing dependence upon the automobile.
9. Revenues and resources can be shared more cooperatively among the municipalities and centers within regions to avoid destructive competition for tax base and to promote rational coordination of transportation, recreation, public services, housing, and community institutions.

7.4.2 Monetization of Ecological Services

An additional consideration in accurate selection of the decision domain for the decision model is the opportunities that arise for monetization of ecological services. Throughout the first part of the 20th century, there was almost no monetization of services provided by natural systems. That began to change significantly in the 1950s with the advent of environmental regulations that restricted the use of rivers and land for large-scale disposal of waste. These regulations expanded dramatically in the 1970s with the advent of federal laws such as the National Environmental Policy Act, the Clean Air Act, and the Clean Water Act, which created a de facto monetization of ecological services by forcing their users to internalize the costs. Regulation of disposal practices recognized air, groundwater, rivers, and certain aspects of the land as part of the public commons.

Another phase in the monetization of ecological services is occurring with the introduction of policies intended to reduce greenhouse gas emissions and enhance the development of renewable energy. Initiatives such as these will increase opportunities for using market forces to expand the decision domain for land use decisions. How they will affect the establishment of decision domains is reviewed in the following sections. For a more detailed discussion of ecosystem services valuation refer to Chapters 24 and 25.

Carbon Sequestration

Greenhouse gas emission control will provide alternative income streams for land holdings that otherwise would have market value dominated by forms of ecosystem mining, especially in areas where land is rapidly being converted from agriculture or forestry to development. As identified by Lal (2004), the carbon sink capacity of the world's agricultural and degraded soils is significant, and sequestration of carbon may have the additional benefit of increasing agricultural yields. Strategies for expanding the soil carbon pool may also help to achieve the objectives of sustainable development. These strategies provide land use planners, landowners, and investment capitalists with additional land use decision options. Land management activities (e.g., soil restoration and woodland regeneration, no-till farming, cover crops, nutrient management, manure and sludge application, improved grazing, water conservation and harvesting, efficient irrigation, agro-forestry practices, and growing energy crops on spare lands) have societal value. As land activities such as these are monetized for their sustainability benefits, decision makers will have available expanded decision domains. For a more detailed discussion of greenhouse gas sequestration, see Chapter 19.

Renewable Energy

The demand for renewable energy has the potential for radically expanding the decision domain for land use and resource management. Legislative activity at the federal and state levels as of 2009 is targeted toward replacing 15 to 20 percent of current energy use with renewable energy. In the 2007 and 2008 legislative sessions of Congress, more than 460 bills on energy efficiency and renewable energy were introduced (Congressional Research Service, 2008). Of these, approximately one-third were focused on renewable fuels. Specific action has been in place since 2005 by the Department of Defense, in accordance with a 2007 Executive Order, to obtain 50 percent of the renewable fuel used per year from new sources and to increase the percentage of renewable fuel use from 3 percent in 2007 to 7.5 percent by 2013 (Bush, 2007).

An example of action at the state level is California's Renewables Portfolio Standard (RPS) program (State of California, 2002). This program requires retail sellers of electricity to increase their sales of eligible renewable energy sources by at least

1 percent of retail sales per year, so that 20 percent of retail sales will be served by eligible renewable energy resources by 2010. Governor Arnold Schwarzenegger set a longer-term state goal of 33 percent by 2020. Twenty-seven states have adopted similar RPSs (Energy Efficiency and Renewable Energy, 2009). In Europe, the European Parliament has adopted an overall target of 20 percent use of renewable energy, with a directive to member states to develop their own targets to help reach this goal (European Parliament, 2008).

These initiatives will increase demand and create associated income streams for alternative land uses associated with renewable energy, particularly biomass. Biomass energy is derived from three distinct sources: wood, waste, and alcohol fuels (Energy Information Administration, 2007). Wood energy is derived both from direct use of harvested wood as a fuel and from wood waste streams. Biomass alcohol fuel, or ethanol, is currently derived almost exclusively from corn in the United States. However, extensive research is under way in the development of technologies for converting a wide range of plant- and animal-based materials to liquid fuels.

The ongoing initiatives in the United States are attempts to increase the use of renewable sources of energy from the current 7 percent (see Figure 7.8) to greater than 15 percent. This will dramatically change the demand conditions for various land uses. In addition, it will divert significant wealth streams, many of which are currently moving offshore for the purchase of foreign oil, to opportunities for alternative land and resource management.

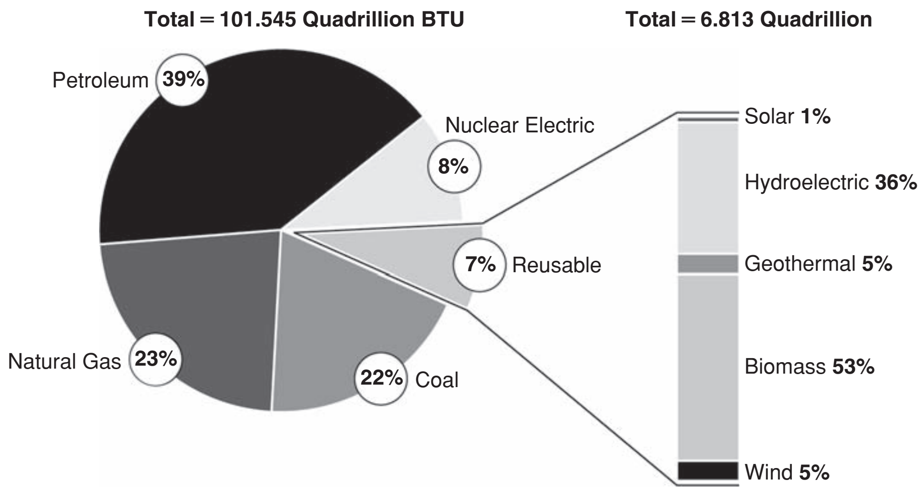

FIGURE 7.8

The initiatives underway are attempting to increase the use of renewables from the current 7 percent to greater than 15 percent.

7.5 BASIC DECISION TREE FORMS

There are several basic forms of decision, uncertainties, and outcomes that might be encountered in various combinations in any decision setting. Clemen (1996) identified basic decision/consequence settings:

- Basic risky decision
- Double risk decision
- Range of risk
- Imperfect information
- Sequential decision

7.5.1 Basic Risky Decision

The basic risky decision is shown in Figure 7.9. In this example, the decision maker has the choice between a certain and an uncertain outcome. In our land use example of the previous section, if the land is sold, the income is certain. The alternative to selling is to keep the land and manage it for a variety of uses. As discussed earlier, the landowner may be able to generate income by engaging in various forest or agricultural activities as well as selling carbon credits or taking advantage of incentives for the provision of biomass for renewable energy. The income streams from these alternatives are uncertain, as they are dependent on future market forces.

In Figure 7.9, the objective is maximizing economic benefit, and the performance metric is the net present value. Other performance metrics and objectives can be identified that capture a fuller range of the decision maker's decision

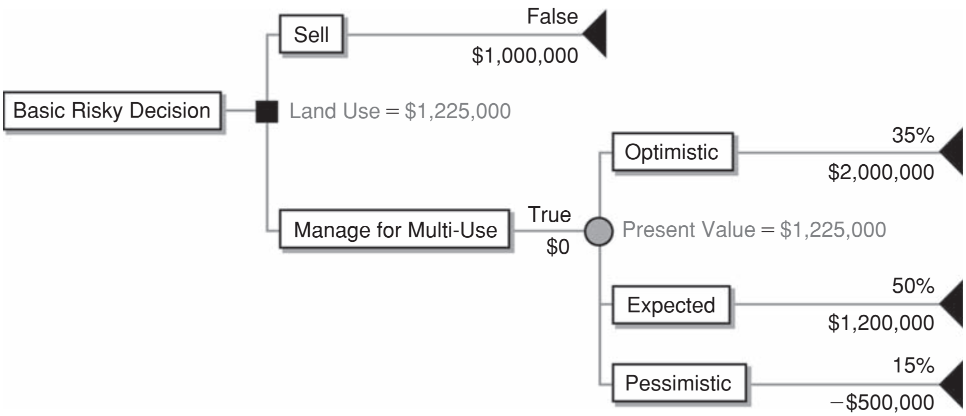

FIGURE 7.9

Basic risky decision.

setting. These include individual or collective quality of life and environmental sustainability. Multiple performance metrics may be defined for each objective. For economic considerations, they can include cash flow, achieving a cap on potential loss, timing of income, and the like. The expansion of a decision tree model to multiple objectives is discussed more fully in Chapter 8.

Figure 7.9 indicates that the landowner knows that the present value of selling the land is a million dollars. If she elects to manage the land instead, she faces a range of outcomes. Let's assume for this discussion that based on her research into market conditions, the time at which she brings the land's resources to market, and the investment requirement, the expected present value is \$1.2 million. However, there is a high potential of greater benefit. For example, the landowner knows that plans are under way for construction of a biomass-to-energy power plant within fifty miles of her property. If this plant is constructed, a new income stream will be available from the slag left in the forest after the property is timbered. In addition, she knows that a cooperative is forming to certify forest management practices to obtain tradable carbon sequestration credits.

However, there is also the potential for significant loss. Managing the property requires significant capital outlays, and most of the income streams will not commence for a decade. Although the probability of a collapse in various markets might be low, it is possible that when the landowner is ready to market her timber, demand will have diminished or even collapsed. She knows that bad timing could affect the outcome for each of the potential income streams: saw timber production, biomass-to-energy sales, and carbon sequestration credits.

Each branch on the lower branch of the decision tree has two input values. One is the probability of the particular outcome and the other is the value associated with that outcome. The probabilities satisfy the requirement identified earlier in this chapter that each branch have a probability value of between 0 and 1.0, and the branches sum to 1. The value of the risky decision is the sum of the products of each branch's probability multiplied by its value:

$$(\$2,000,000 \times 35\%) + (\$1,200,000 \times 50\%) + (-\$400,000 \times 15\%) = \$1,225,000$$

In the basic risky decision, the decision maker must consider not only the expected outcome—in this case \$1,225,000 if the land is maintained and managed—but also the tolerance for loss. The landowner has a chance of doubling the value of the land but also a chance of losing \$400,000. Is the much greater chance of significant return worth the potential loss of \$400,000? That will depend to a large extent on the marginal value of the extra \$1,000,000 versus the marginal value of the loss of \$400,000. If the landowner does not have the resources to sustain the loss, then the loss has a much higher marginal impact than a gain of \$1,000,000.

As will be discussed in Chapter 8, other objectives involving sustainability should come into play. The landowner can expand the decision context to include social and environmental responsibility as objectives, and can open up additional strategies. In this particular risky decision setting, the landowner's major difficulty is the chance of a loss versus a sure thing, and perhaps the issue of cash flow. Through the introduction of other sustainability objectives, thinking expands to include strategies for mitigating the downside. An example is the use of conservation easements that allow the uses of the property as envisioned but reduce taxes, or the augmenting of cash flow from entities, public or private, that are targeting land preservation.

7.5.2 Double Risk Decision

The basic form of the double risk decision is shown in Figure 7.10. It is a variation of the basic risky decision in which the choice is between two risky decisions. The decision maker can win or lose either way. The example given in Figure 7.10 expands on the landowner's situation just described. Imagine that, instead of a straightforward sale of the property, the $1,000,000 represents a share of the profit that can be derived from developing it. There is a possibility, though, that the development will not meet expectations and will barely break even. In such a case the landowner may see a greatly diminished return.

In the basic risky decision discussed previously, the marginal economic benefit of managing the property for its forest or agricultural resources may not have been viable given the associated cash flow and potential for significant loss. In the

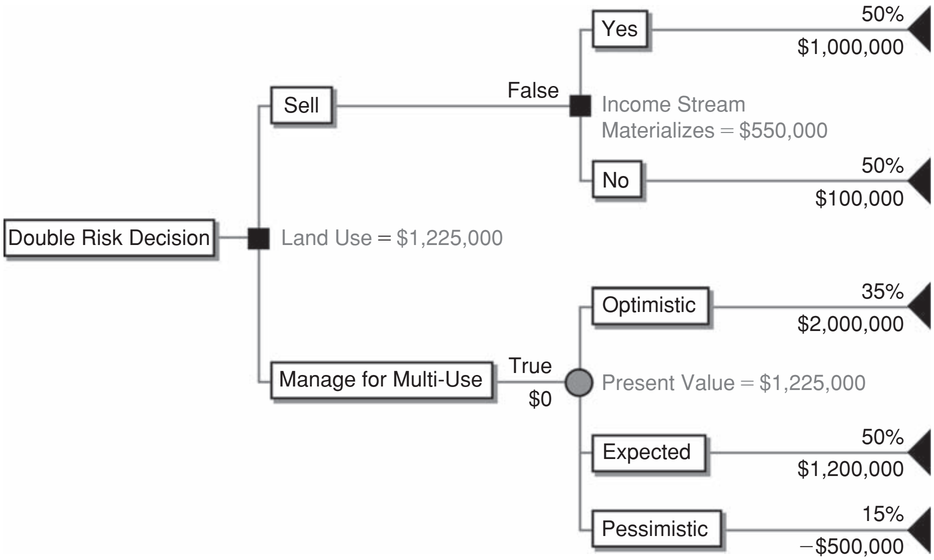

FIGURE 7.10

Double risk decision.

double risk example, the marginal economic benefit spread between alternatives is wider. In considering the risk associated with both alternatives, the decision maker has incorporated a fuller picture of the decision context.

This example is a simplification of the issue, but in many large-scale resource management cases, the decision is approached as if it were the basic risky decision form when in reality it is a double risk form. This is particularly true when the outcome of a proposed activity is assumed, erroneously, to be a given as opposed to an uncertainty. In addition, when the multiple objectives of sustainability are taken into consideration, most decision settings involve the double risk form.

7.5.3 Range of Risk

In the range of risk form, the chance event can take on any value within a range of possible values. This form is shown in Figure 7.11, where, instead of the fixed outcomes shown in Figure 7.10, the outcome is a continuous variable. The

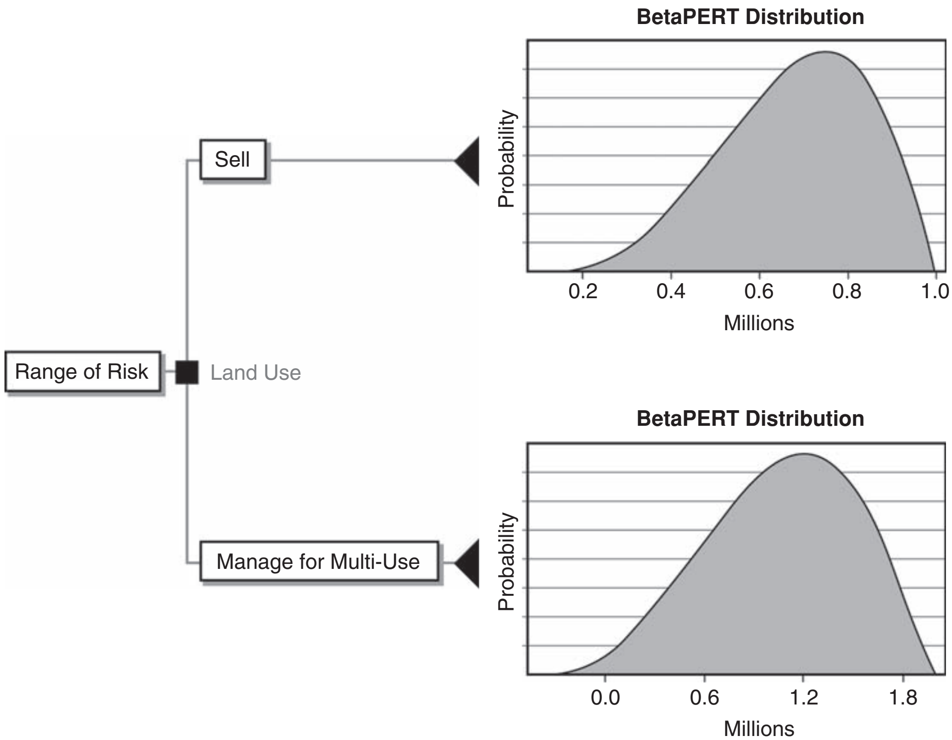

FIGURE 7.11

Range of risk.

distribution can take many forms, from a straight line to various distributions that weight the outcomes in accordance with the decision maker's understanding of probabilities. In the example shown in Figure 7.11, the distributions are weighted most heavily toward the expected value for each of the branches. For the "sell" branch, the most likely outcome is $750,000. However, the actual outcome could fall anywhere between $100,000 and $1,000,000. For the "manage for multi-use" branch, the most likely outcome is $1,200,000. The actual outcome, though, could fall anywhere between a loss of $400,000 and a gain of up to $2,000,000. The decision maker in this case, rather than looking at just the expected outcome, has a relative profile of the liability and benefit between the two options.

A profile of the landowner's liabilities and values for the two alternatives is shown in Figure 7.12, where the curves are cumulative plots of the distributions in Figure 7.11. They are generated by summing the probabilities under the distribution curves and plotting them against the corresponding dollar return. Figure 7.13 shows the calculation. The curves indicate the probability that the net income will be equal to or less than a given dollar value.

The curves represent a snapshot of the consequences of the decision branches, allowing the decision maker to grasp the essence of the decision's consequences. The curves provide several critical pieces of information. The first is the uncertainty that will be inherent in a particular choice. The steeper the slope of the

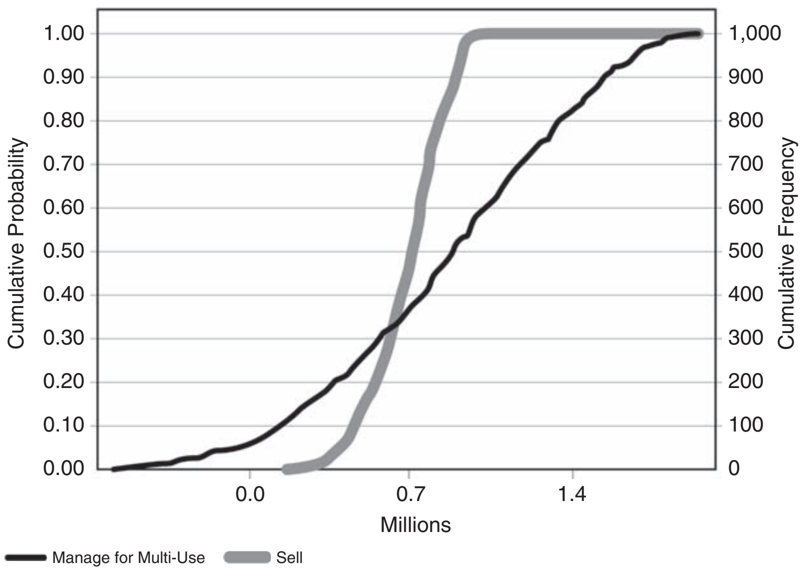

FIGURE 7.12

Liability/value profile.

Percentile Interval	Value	Cumulative Percentile
4%	$100,000	4%
6%	$450,000	10%
10%	$550,000	20%
12%	$625,000	32%
14%	$700,000	46%
14%	$750,000	60%
12%	$800,000	72%
10%	$850,000	82%
8%	$875,000	88%
6%	$900,000	94%
6%	$1,000,000	100%

FIGURE 7.13

Example of the calculation using Figure 7.12.

liability/value profile, the less uncertainty is associated with that choice. Conversely, the flatter the slope of the liability/value profile, the greater the uncertainty. The second vital piece of information in the curve is the realistic range of outcomes. From this information the decision maker can determine at a glance the likelihood that his tolerance for loss has an acceptable probability. Finally, the liability/value profile provides an idea of the premium that is paid for certainty. In Figure 7.12, the choice to sell the property has a 50 percent probability of costing the landowner several hundred thousand dollars. There is some chance that the cost could rise to $700,000 or more. However, the landowner buys certainty that there will not be a net loss.

The liability/value curves also offer a means for engaging in critical analysis of the decision tree and influence diagram to identify opportunities to alter the decision setting. The profiles provide an understanding of how the alternatives compare in terms of the decision maker's risk tolerance in achieving his objectives. With this knowledge, the underlying uncertainties within the decision tree can be assessed to determine if the uncertainty drivers can be altered or managed. The goal is to determine if the liability/value profiles are sensitive to uncertainties that can potentially be resolved or at least made less severe. The example discussed earlier uses the net return in dollars as the performance metric. Note that the performance metrics, and the associated liability/value profiles, can be established for each of the objectives in a given decision context.

7.5.4 Imperfect Information

In some instances, a decision maker is either waiting for the information before making a decision or needs to determine if the uncertainty can be managed sufficiently so as not to alter the subsequent decision paths. An example of imperfect information as represented in a decision tree is shown in Figure 7.14. In this

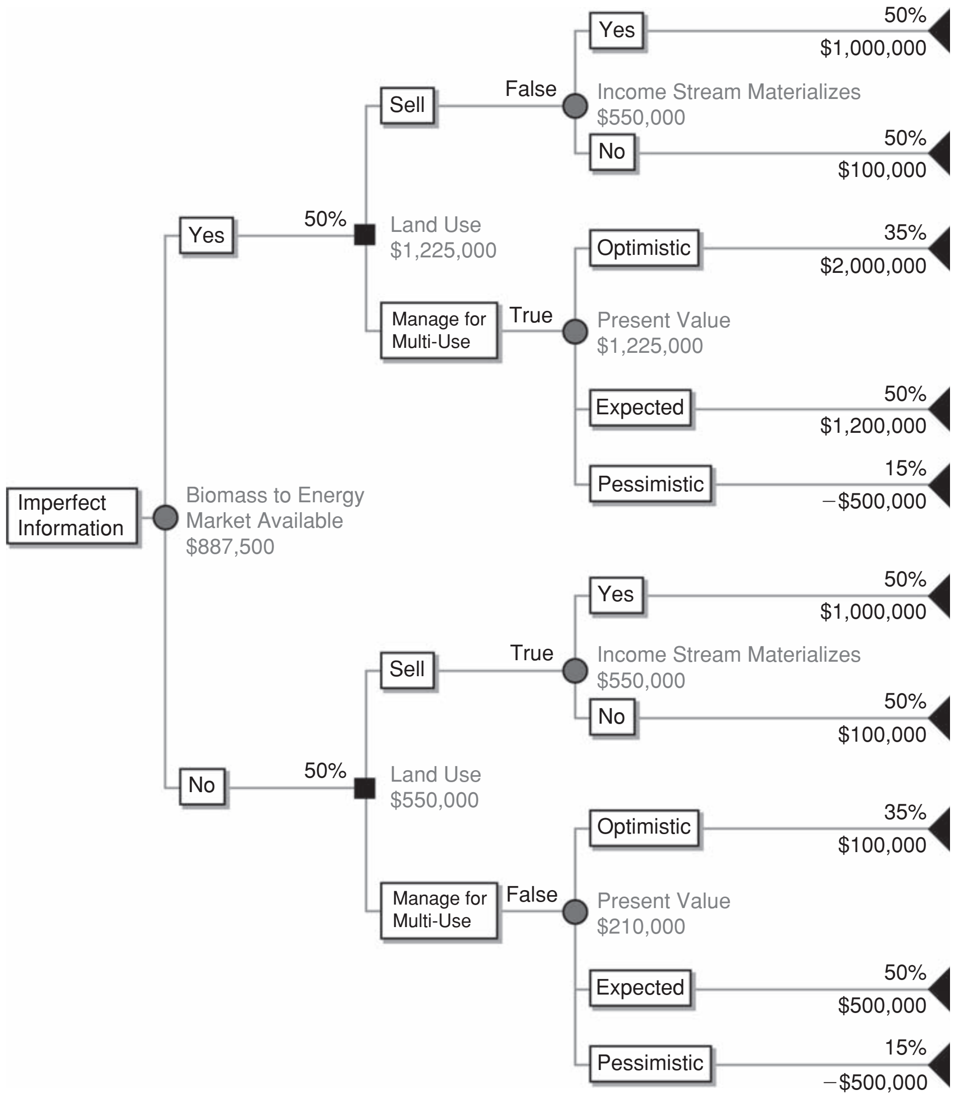

FIGURE 7.14

Imperfect information.

example, the landowner's ability to manage the land for multi-use purposes will be impacted significantly by whether or not a biomass-to-energy power plant is constructed within fifty miles of her property. In the example shown, at least with respect to the economic objective, the decision either to sell or to manage is sensitive to whether or not the plant is constructed. With the assumptions underlying the analysis in Figure 7.14, the landowner is better off, economically, selling the property if the alternative income streams do not materialize. In this instance, the available information is insufficient to make a decision.

Imperfect information does not have to be turned into perfect information or resolved before a decision is made. In most decision settings there will be extensive imperfect information. However, if a chance node is chronologically sequenced before a decision node, there is an uncertainty that must be managed in some fashion in order to make a sound choice.

7.5.5 Sequential Decisions

Sequential decisions are those that are contained within the same decision setting or that have to be addressed in a unified manner. Often sequential decisions can only be resolved by establishing an overall strategy that examines the dynamic interaction of the sequential decisions. An example is shown in Figure 7.15 for

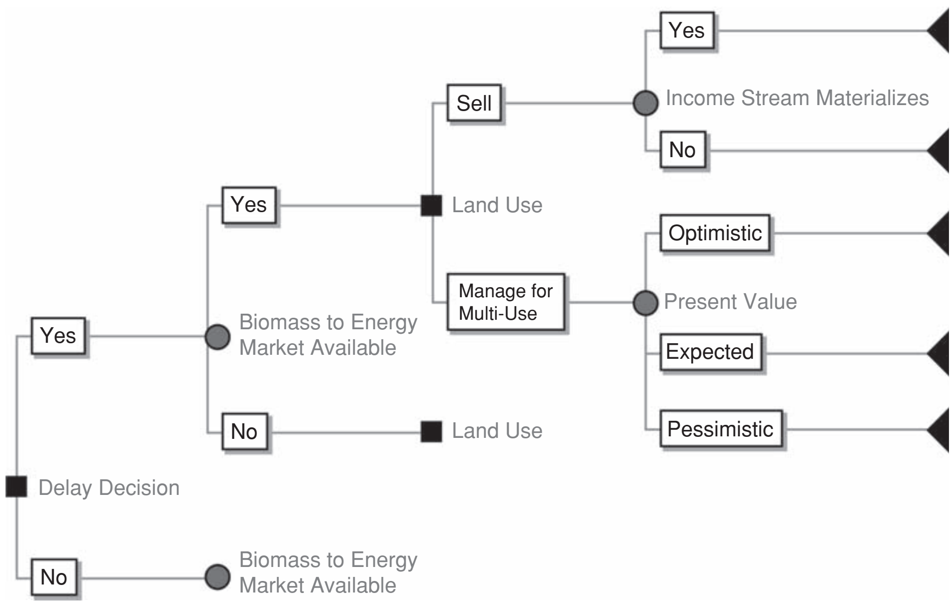

FIGURE 7.15

Sequential decisions.

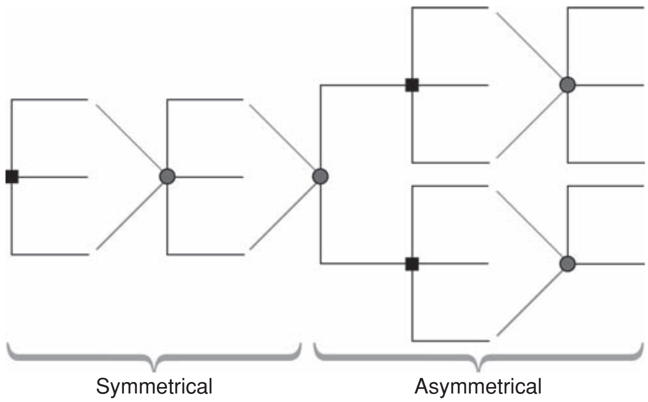

FIGURE 7.16

Schematic form of symmetrical decision tree.

our landowner's decision setting. The first decision might be whether or not to wait before making subsequent decision. The remainder of the decision tree could be worked through, with contingencies developed that are dependent on the outcome of the initial uncertainty regarding the availability of alternative income streams.

Because the number of branches can grow exponentially, sequential decision settings can rapidly become unwieldy. As the branches grow, several methods can be employed to keep the model manageable. The first is demonstrated in Figure 7.15, where subsequent branches are collapsed and one branch is assessed at a time. If the outcomes are symmetrical, meaning that the subsequent nodes are the same regardless of the branch of a particular uncertainty (the activities are the same, not the outcomes), the tree can be demonstrated in schematic form as shown in Figure 7.16.

The other technique is to break the tree into distinct blocks that each represents decision milestones. Generally, these will be blocks of information decisions, fundamental decisions, and implementation decisions.

7.6 CONCLUSION

The decision tree and the decision uncertainty trees, coupled with influence diagrams, graphically model a decision setting. Such models are the basic tools that a decision team can use to understand the interaction between input variables, information, core and implementation decisions, and associated uncertainties. Techniques for assessing and comparing the consequences of decisions are discussed in Chapter 9.

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CHAPTER

Multi-Objective Modeling

8

William L. Hall

8.1 INTRODUCTION

As discussed in Chapter 7, decision makers should determine the appropriate scale for a decision by evaluating temporal and spatial factors. Likewise, objectives and their associated metrics should be determined in light of scale. At the simplest scale, there is a single economic objective, such as maximizing return on investment. But even with only a single economic objective, there may be multiple performance metrics. Our landowner, for example (from Chapter 7), clearly has one distinct economic interest: maximizing her return on investment. The other economic interests, though, are the probability and magnitude of loss, the magnitude and probability of maximum return, and cash flow.

As soon as more than one criterion comes into play, we must address all criteria comprehensively to compare potential actions. Frequently we encounter a situation where two or more alternatives under consideration have differing performance characteristics for the various objectives. In our rezoning scenario from Chapter 7 approval of the development may provide the most attractive short-term benefit in terms of new construction jobs, sales commissions, and tax revenues for the county. But there may also be long-term liabilities in increased infrastructure costs, reduced availability of water supplies, and/or increased costs for social services such as schools. Which is more important, the short-term benefits or the long-term costs? These objectives conflict not only in time frame but also in terms of who bears the cost and who obtains the benefit. Of the alternatives available, some will better satisfy certain objectives, while some will better satisfy others.

The challenge, especially with the complexity and uncertainty inherent in the broad scale of sustainability, is to obtain a comprehensive judgment. This comprehensive judgment tries to take into account, in a holistic manner, the performance of each alternative against each objective at the appropriate temporal and spatial scale.

DOI: 10.1016/B978-1-85617-797-9.00008-3

8.2 MULTI-CRITERIA DECISION ANALYSIS

Multi-criteria decision analysis (MCDA) provides an overall ordering of options, from the most to the least preferred. It is a way of examining complex problems that contain a mixture of monetary, societal, and environmental objectives. Data and judgment are applied to the individual objectives and then aggregated to present a coherent overall picture to decision makers. The purpose is to serve as an aid to thinking and decision making. Extensive research has been conducted, starting in 1976 with Keeney and Raiffa's work in numerical techniques for handling MCDA.

Conversion of the multiple levels of values into a mathematical construct, however, is unworkable in practice. Nevertheless, decision makers can unpack their relative values and the relevant forcing functions of those values. These forcing functions arise from individuals' conceptual models of how the world should work. Those models in turn are built on personal experience, perspectives, and heuristics, and are colored by how each individual balances self-interest and present and future social obligations. Social obligations are the ultimate source of environmental consciousness, as they are the mental wiring that both allows and drives us to envision a future beyond the horizon.

The key feature of MCDA is its unpacking and documentation of the judgment of the decision makers in establishing the relative importance weights and, to some extent, in judging the contribution of each option to each performance criterion. If applied with methodical thoroughness, MCDA provides structure and openness to decisions regarding sustainability that traditional one-dimensional cost–benefit analysis cannot provide.

8.3 PERFORMANCE MATRIX

The workhorse of MCDA is the *performance matrix*, or consequence table. An example is shown in Figure 8.1 for the development of the 10,000 acres that we examined from the perspective of a zoning board (Chapter 7). To explore MCDA techniques, we are now going to examine this project from the perspective of the landowner. We are assuming, for this discussion, that the landowner is approaching the decision at the scale of sustainability and not from the perspective of simple maximization of short-term net income.

In Figure 8.1, each row describes an alternative and each column describes the performance of the alternative against each objective. The simplest level of comparison is a ranking of the alternatives with respect to each of the objectives. The decision tree shown is the simplest possible; there is no attempt to incorporate in it the unique combinations of uncertainties associated with each alternative.

Some explanation of the structure of the MCDA model shown in Figure 8.1 is necessary. The objectives are broken into three classes: economic, social, and

Land Use	Decision	Option	Economic Indicators: Short-Term Net Income	Economic Indicators: Long-Term Net Income	Economic Indicators: Potential of Debilitating Loss[1]	Social Indicators: Family Integrity[2]	Social Indicators: Family Influence[3]	Environmental Indicators: Ecosystem Integrity	Environmental Indicators: Closed Loop Energy/Waste Flows
Sell	Conservation Easements	Yes	6	1	7	2	2	4	2
Sell	Conservation Easements	No	7	2	6	1	1	1	1
Develop New Urbanism	Density	High	5	6	1	5	7	2	3
Develop New Urbanism	Density	Medium	4	5	2	4	6	7	5
Develop New Urbanism	Density	Low	3	3	5	3	4	6	6
Multi-Use	Renewable & Carbon Credits	Yes	1	7	3	7	5	5	7
Multi-Use	Renewable & Carbon Credits	Conventional AG Practices	2	4	4	6	3	3	4

[1] Debilitating loss defined as a single year loss > $50,000 or total five-year loss greater than $300,000

[2] Family integrity defined as capacity to create multi-generational transfer of wealth, opportunity, life experience, and cohesion

[3] Family influence as the impact of multiple generations on the social and power structures of the community

FIGURE 8.1

Performance matrix.

environmental. These capture the fundamental requirements of sustainability. The meaning of these three fundamentals is specific to the situation and varies among decision makers. The meaning for the zoning board can and probably will be radically different from that for the landowner.

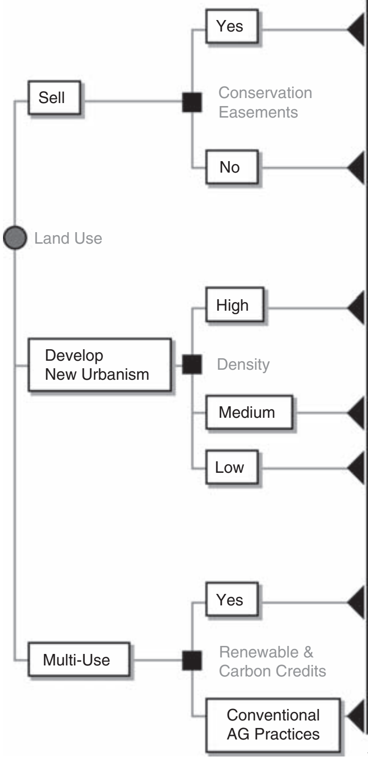
In our imagined situation, the landowner has specific objectives or needs within each of the three fundamental areas. In the economic realm, she will have interest in maximizing income, but that need will be balanced by her tolerance for loss and her ability to maintain cash flow. Adding the social and environmental realms into this decision setting provides the framework to more accurately isolate and characterize what are generally nonmonetized objectives. Social and environmental objectives may be motivated primarily by self-interest, but can still be targeted toward sustainability. Such objectives may include the impact of the decision on the landowner's family in the future or a desire to leave some meaningful footprint on the world after death. They may also include the philosophical or emotional objective of stewardship of natural systems that transcends strict self-interest.

8.4 QUALITATIVE POPULATION OF PERFORMANCE MATRIX

Alternatives can be ranked using different levels of complexity. The approach shown in Figure 8.1 is a simple ordering of each alternative with respect to each objective. The individual performance assessments may also be expressed as "bullet point" scores or color-coded, and they may include qualitative information regarding threshold conditions or qualitative judgments. In this basic form of MCDA, the performance matrix may be the final product of the analysis. Decision makers can then rely on the matrix as they consider their choices qualitatively using facilitation techniques such as those discussed in Chapter 21. Such intuitive processing of data and information is analytically simple, readily accessible to any participant, and understandable. It has the disadvantage of not providing a rigorous means for disaggregating the beliefs underlying the ranking. Thus, it is highly susceptible to providing little more than a matrix of psychological traps, incomplete understanding, and flawed assumptions.

At the next level of complexity, each alternative is scaled for each of the objectives based on the relative qualitative characteristics of the alternative. An example is shown in Figure 8.2. In this approach, the expected consequences of each alternative are assigned a numerical score, developed using a strength-of-preference approach to generate a scale for each alternative for each criterion. More preferred alternatives score higher on the scale; less preferred alternatives lower. Any scale can be used, but in practice it needs to be large enough to allow flexibility in spreading the strength of preference. Scales extending from 0 to 100 are typical, where 0 represents a real or hypothetical least preferred alternative and 100 represents a real or hypothetical most preferred alternative. All alternatives considered in the MCDA thus fall between 0 and 100 (Figure 8.2).

Keeney (1992) detailed a number of techniques for developing qualitative numerical values in a performance matrix. The more common techniques involve various forms of polling. One creative approach is preference auctioning, in which participants are first given a fixed number of points for achieving each objective. These points are then used to "bid" for a particular alternative.



Alternative	Economic Indicators			Social Indicators		Environmental Indicators	
	Short-Term Net Income	Long-Term Net Income	Potential of Debilitating Loss[1]	Family Integrity[2]	Family Influence[3]	Ecosystem Integrity	Closed Loop Energy/ Waste Flows
Sell – Conservation Easements: Yes	84	14	98	28	28	56	28
Sell – Conservation Easements: No	98	28	84	14	14	14	14
Develop New Urbanism – Density: High	70	84	14	70	98	28	42
Develop New Urbanism – Density: Medium	56	70	28	56	84	98	70
Develop New Urbanism – Density: Low	42	42	70	42	56	84	84
Multi-Use – Renewable & Carbon Credits: Yes	14	98	42	98	70	70	98
Multi-Use – Conventional AG Practices	28	56	56	84	42	42	56

[1] Debilitating loss defined as a single year loss > $50,000 or total five-year loss greater than $300,000

[2] Family integrity defined as capacity to create multi-generational transfer of wealth, opportunity, life experience, and cohesion

[3] Family influence as the impact of multiple generations on the social and power structures of the community

FIGURE 8.2

Scaled performance matrix.

8.5 QUANTITATIVE POPULATION OF PERFORMANCE MATRIX

One of the most rigorous methodologies for populating the performance matrix is known as the decision consequence approach. As introduced in the discussion on constructing decision models in Chapter 7, decision models incorporate the uncertainties in the numerical measurements of an alternative's performance.

An analytical model is constructed by developing a metric for each of the objectives. Chapter 9 provides a more detailed discussion of the development of an analytical model. A few examples are given here for our decision setting—the landowner trying to decide whether to sell or to manage her 10,000 acres.

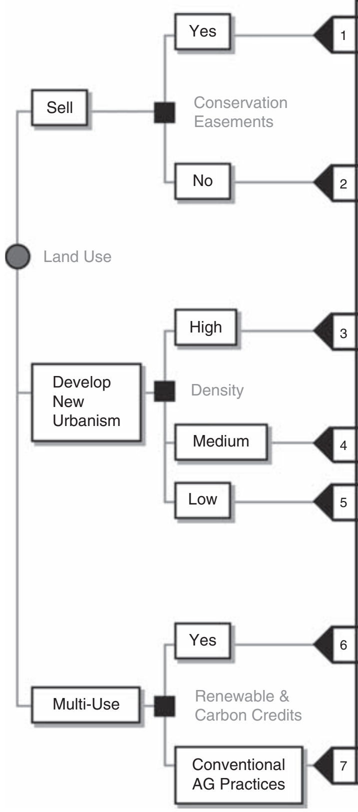
Economic metrics appear to be the most straightforward in this scenario. However, among the potential measures of economic performance, the landowner will likely need to balance her desire for long-term maximization of net income with the short-term cash flow issues. In addition, she should not pursue long-term objectives without protecting herself against short-term disaster. The objective of long-term sustainability, whether economic, social, or environmental, will have little chance of being achieved if the landowner is unable to maintain economic viability. The three economic metrics applied in this example to capture this balance are (1) short-term cash flow (net return within the next five years), (2) long-term cash flow (long-term annuity), and (3) risk probability (probability of debilitating negative cash flow).

Each alternative will have a specific cost, income, and risk profile. A sample is shown in Figure 8.3. These inputs are a function of the variety of uncertainties that will affect the performance metric. A representative set of the inputs that can be used to develop the metric of short-term cash flow is shown in Figure 8.4. Each input is an uncertainty. These uncertainties can be combined into a fuzzy set, which can be used as a probabilistic tool for assessing performance. A similar breakdown of inputs can be developed for each of the performance metrics.

The fuzzy set concept incorporates the fact that, despite the depth of experience a decision-making team may bring to a decision setting, it cannot predict the future. In any decision setting, we have at our disposal evidence from the past, data regarding the current reality, and physical constraints dictated by the natural world. All of these inputs are shaped and given boundaries by individual and collective judgment. Unfortunately, they are also subject to the full range of psychological traps as discussed in Chapter 4.

There are ample statistical procedures for extracting the patterns of activities within the natural and sociopolitical world that govern a particular variable. But they all operate under the common assumption that past patterns give valid insight into the trajectory of change as we move into the future. Predictions regarding the trajectory of change are nonprecise. As shown in Figure 8.5, a performance metric need not be a number but can be a distribution. It is desirable to break down the performance metrics into their component parts. The finer the breakdown of variables, the more robust the definitions of their uncertainty profiles. As the quality of the input uncertainty profiles improves, so does the performance metric profile, and the performance metric will be less likely to have judgment failures. The multiple variables that affect a performance metric are combined using techniques such as Monte Carlo analysis (Chapter 10).

The values shown in Figure 8.5 may be characterized by a variety of distributions, from a simple straight line to various skewed distributions. Such skewed distributions (see examples in the figure) provide a way for decision makers to



	5-Year Cost Outlays				5-Year Income				Total Net Income	
	Max	Min	Expect	Variable	Max	Min	Expect	Variable	Yearly	Total
1	$400,000	$100,000	$250,000	$250,000	$1,500,000	$100,000	$750,000	$750,000	100,000	$500,000
2	$100,000	$50,000	$75,000	$75,000	$1,200,000	$0	$500,000	$500,000	85,000	$425,000
3	$1,000,000	$400,000	$600,000	$600,000	$3,000,000	$50,000	$1,000,000	$1,000,000	80,000	$400,000
4	$750,000	$250,000	$400,000	$400,000	$2.250,000	$50,000	$1,000,000	$1,000,000	120,000	$600,000
5	$400,000	$100,000	$300,000	$300,000	$1,500,000	$50,000	$800,000	$800,000	100,000	$500,000
6	$500,000	$400,000	$425,000	$425,000	$600,000	$0	$100,000	$100,000	−65,000	$325,000
7	$500,000	$400,000	$475,000	$475,000	$600,000	$100,000	$500,000	$500,000	5,000	$25,000

FIGURE 8.3

Decision consequence analysis for example objective performance matrix.

incorporate a range of likely outcomes while also capturing the belief that there is one outcome that is more likely than the others.

The qualitative, quantitative, or mixed population of values in a performance matrix provides the comparison tool for understanding how the objectives interact. The decision-making team must collectively balance the achievement of the objectives. This balancing will require an understanding of the relative importance of objectives. Decision makers need a high level of self-awareness coupled with the ability to escape psychological traps.

There are two basic approaches for dealing with multi-objective decision settings in which mutually exclusive or conflicting objectives must be

FIGURE 8.4

Influence diagram for developing distribution of costs.

balanced: relational and aggregational. The relational approach is a stepwise procedure in which objectives and alternatives are qualitatively compared. It does not join the differing objectives to a common measure of success. The aggregation approach, in contrast, creates a common performance metric. An example of this approach is the triple bottom line accounting procedure, discussed in Chapters 3 and 25, which monetizes societal and environmental services to create a single measure of the economic, social, and environmental consequences of a decision.

Both approaches have disadvantages. The relational approach, with its reliance on qualitative comparison, can be dominated by the strongest personalities on the decision team; the aggregational approach creates the illusion of numerical rigor when in fact any algorithm developed for combining disparate objectives can be gamed if certain decision makers want to achieve a preconceived outcome.

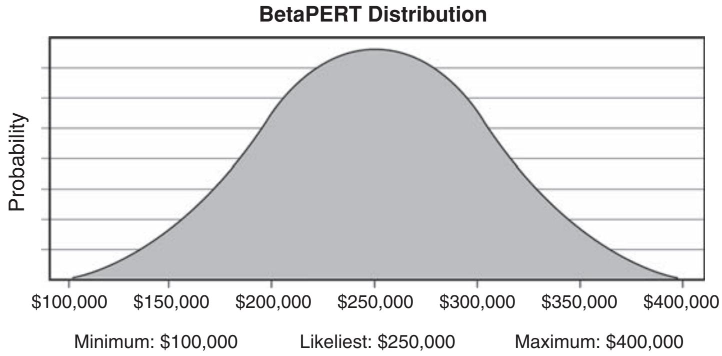


FIGURE 8.5

Example fuzzy variable for uncertainty of first five years of costs associated with alternative 3 of the Figure 8.3 performance matrix.

These problems are real and unavoidable, as the very existence of a decision setting means that there is uncertainty regarding an important issue and that human judgment is necessary.

However, both approaches provide the decision team with a platform for uncovering differing values and attitudes toward risk. They also help capture individual experience and explore how it can establish boundaries for uncertainties. In addition, and of equal importance, the two approaches provide rigorous process documentation. A good decision process does not guarantee a good outcome. The ability to revisit and unpack a decision process is central to achieving sustainability. It is this ability that permits our decision making to be a dynamic process rather than an event. Large-scale policy and planning decisions affecting land, water, and natural resources should be in dynamic flux, capable of measuring and responding to feedback.

8.6 RELATIONAL PERFORMANCE MATRIX ANALYSIS

The most basic form of performance matrix analysis is a qualitative assessment that uses a combination of judgment and objective balancing to narrow and ultimately select an alternative. Eight sequential steps for conducting a qualitative performance matrix analysis are described in the following subsections.

Step 1: Analysis for Dominance

The initial step in the analysis of the matrix is to determine if any of the alternatives are dominated by the others. This situation occurs when one alternative performs at least acceptably as well as another on all metrics and strictly better than the others on at least one or more. In such a case, the dominated alternative can be eliminated. Obviously the underlying assumptions, scaling, and numerical values must be verified. However, assuming that the inputs were developed with a valid and internally consistent strategy, a dominated alternative is an appropriate candidate for elimination to simplify the selection process.

An example of dominance is shown in Figure 8.6, which plots the qualitatively derived performance metrics shown in Figure 8.2. The first two alternatives perform relatively similarly against the other alternatives. Alternative 1, selling the property with conservation easements, performs better than alternative 2, selling the property with no easements, with respect to five of the seven objectives. Alternative 2 is superior with respect to two of the objectives. The margin of better performance is close. Although these two alternatives are very similar, the conservation easement alternative is significantly better against one objective (ecosystem preservation) and better against all of the social and environmental objectives.

With this in mind, the landowner has a basis for deciding if she should continue to consider a simple sale of the property with no conservation easements given the marginal economic benefits. She also has a basis for determining if it would be appropriate to more thoroughly examine the underlying assumptions to verify if the conclusion regarding the dominance of alternative 2 is truly robust.

An additional candidate for dominance is alternative 6 over alternative 7. Both involve the landowner continuing to engage in active management of the property, either for traditional agriculture or for a combination of agriculture with emerging markets for renewable energy and carbon credits. Expanding the portfolio of land management options is superior to continuing with traditional practices with respect to all but two of the objectives. Portfolio expansion will reduce the

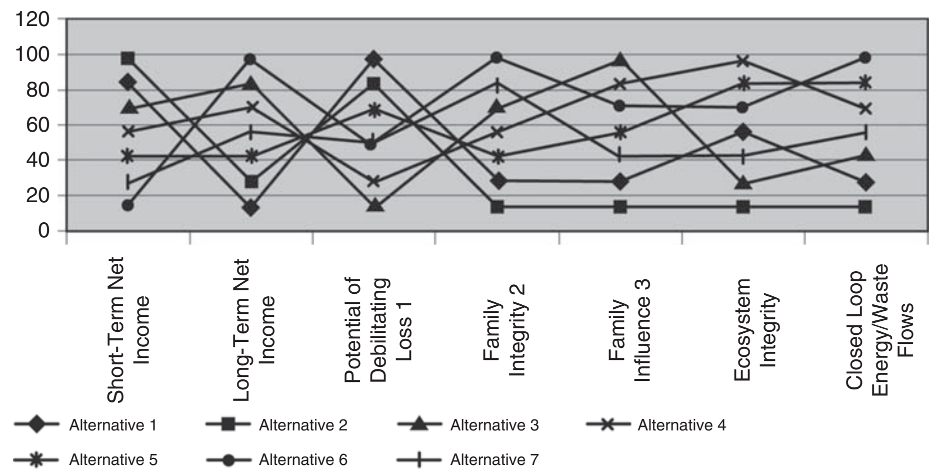


FIGURE 8.6

Example of assessment of dominance.

short-term net income stream. In addition, it presents a slightly greater risk of producing a debilitating loss. Both outcomes are the result of the additional investment that will be needed to enter these nontraditional markets and of the uncertainty regarding how these markets may be priced. However, traditional agriculture itself, either for food crops or wood products, contains a high degree of uncertainty from year to year.

In this example, the landowner has a basis for deciding that her alternatives can be reduced. The two alternatives on the extreme ends of the decision setting—continuing to manage the property for traditional agriculture or a basic fee simple, unrestricted sale of the property—can be eliminated from further consideration. The revised decision tree is shown in Figure 8.7.

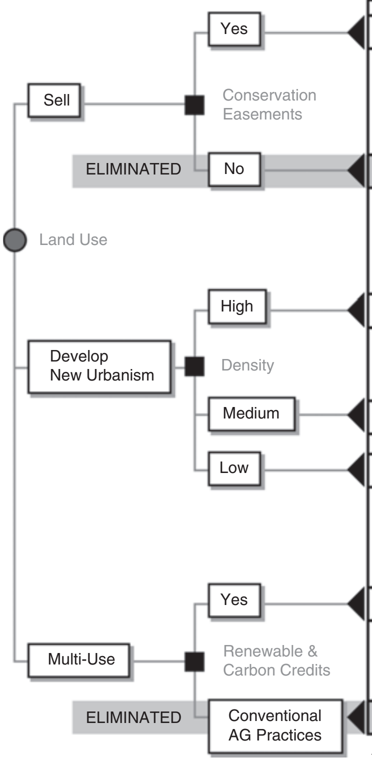
Step 2: Analysis for Fatal Flaw

This step of the analysis examines whether one or more of the alternatives fail to reach a threshold level of acceptability. In this example, it is presented as the second rather than the first step, as it generally requires a more detailed assessment of the performance metrics for one of more of the alternatives.

For our example, the landowner has a primary threshold objective, and that is the ability to maintain sufficient cash flow. No alternative will provide a guarantee because they all carry a risk—even the unrestricted fee simple sale of the property. As long as the landowner has the land, she has a tangible resource. If nothing else it can always provide for her simplest needs of water, food, and shelter. The cash received from the sale is highly liquid and therefore highly susceptible to loss, either in bad investment decisions or because of general economic conditions over which the landowner has no control.

All of the other objectives become meaningless if the landowner faces a debilitating negative cash flow and runs out of the resources to implement her decision. For the economic assessment, a simple scaled comparison is insufficient for the landowner, who needs a more rigorous comparison. A representative assessment of the short-term cash flow issue was discussed in Section 8.5 with sample results shown in Figures 8.3, 8.4, and 8.5.

A probabilistic comparison of the alternatives in terms of yearly net cash flow in the next five years is provided in Figure 8.8; it shows a liability profile of each alternative relative to the particular objective of avoiding a debilitating negative cash flow in any year. The figure requires some explanation. The variables shown in Figure 8.3 define a distribution of potential values for the particular input. Each variable is independent. For example, the landowner's share of developing the land in any year is largely independent of the income and is contingent on many events not under her control. These include the actions of her partners in the development; the zoning difficulties; the competition from other properties on the market; the actions by government entities; and local, national, and international economic conditions.



	Economic Indicators			Social Indicators		Environmental Indicators	
	Short-Term Net Income	Long-Term Net Income	Potential of Debilitating Loss[1]	Family Integrity[2]	Family Influence[3]	Ecosystem Integrity	Closed Loop Energy/ Waste Flows
Sell – Conservation Easements: Yes	84	14	98	28	28	56	28
Sell – Conservation Easements: No (ELIMINATED)	98	28	84	14	14	14	14
Develop New Urbanism – Density: High	70	84	14	70	98	28	42
Develop New Urbanism – Density: Medium	56	70	28	56	84	65	70
Develop New Urbanism – Density: Low	42	42	70	42	56	60	84
Multi-Use – Renewable & Carbon Credits: Yes	14	98	42	98	70	58	98
Multi-Use – Conventional AG Practices (ELIMINATED)	28	56	56	84	42	42	56

[1] Debilitating loss defined as a single year loss > \$50,000 or total five-year loss greater than \$300,000

[2] Family integrity and influenced combined

[3] Family influence as the impact of multiple generations on the social and power structures of the community

FIGURE 8.7

Elimination of dominated alternatives.

The range of uncertainty and the impact of the issues just described can be incorporated into variable distributions for the income and cost streams. Combining these through a Monte Carlo assessment as described in Chapter 10 provides the range of outcomes for the negative cash flow that the landowner may face in any one year. The numbers show the probability that the cash flow will be equivalent to or less than the indicated amount for each alternative for each year.

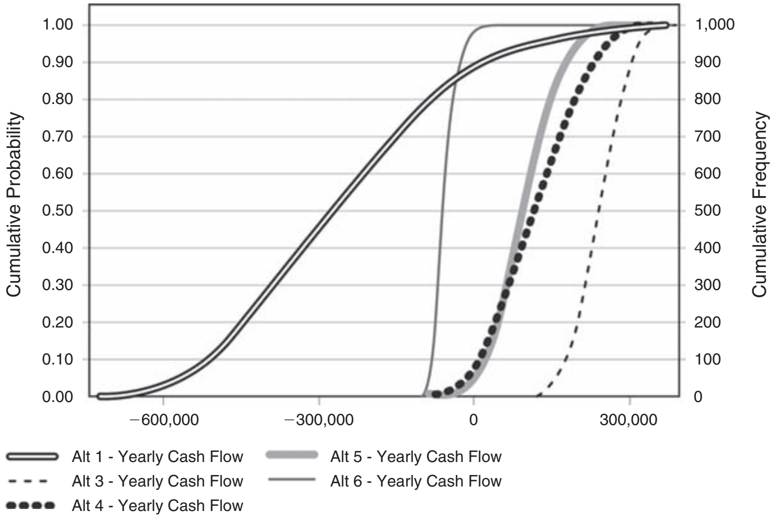


FIGURE 8.8

Liability profile for yearly negative cash flow for performance metric in Figure 8.3—potential for debilitating negative cash flow.

Figure 8.9 is an interpretation of the liability profile for alternative 3. The liability curve demonstrates that the lowest cash flow is estimated to be a negative $700,000. There is a 0 percent chance that the yearly negative cash flow will be worse than this amount. Conversely, there is a 100 percent chance that the cash flow will be less than a positive $620,000. The value of the liability profile is in how the risk is distributed. Note that there is a very high probability that the cash flow will be negative—almost 90 percent. However, negative cash flow is expected in many investment scenarios. The critical issue is the probability that the negative cash flow will overwhelm the landowner's capacity to pay.

For this alternative, the expected negative cash flow (i.e., 50 percent probability) is approximately $262,000. The landowner may be prepared for this and able to sustain it for a period of time. But what if she has a threshold for negative cash flow tolerance of $300,000? At this point, she is facing not only sacrifices in lifestyle but also the potential that she simply will not have the resources to maintain her business. In this example, the probability is quite high, over 40 percent, that this negative cash flow threshold will be realized. Is this a reasonable risk? If there was only a 1 to 5 percent chance of negative cash flow, and the upside potential against other objectives was huge, she might take the risk. But at 40 percent, no upside potential is worth the potential of losing everything she has created to that point.

Besides the economic consideration, the landowner has a threshold requirement regarding the provision of a legacy for her family. Another means of developing a threshold screening criterion, particularly for strictly value-driven objectives, is

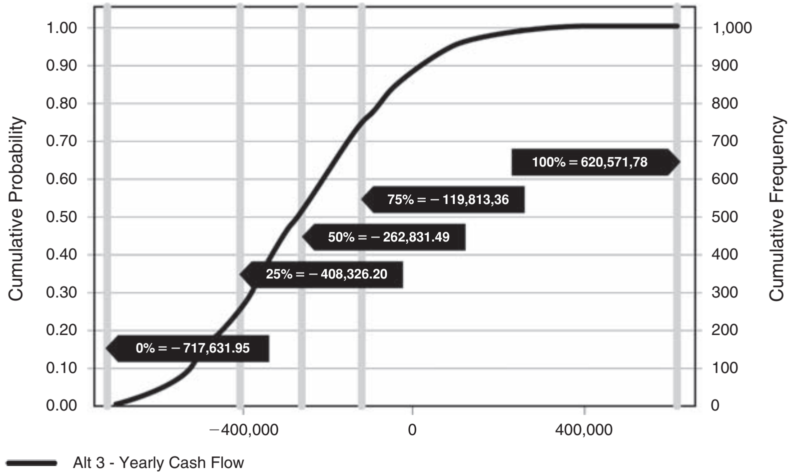


FIGURE 8.9

Interpretation of liability profiles.

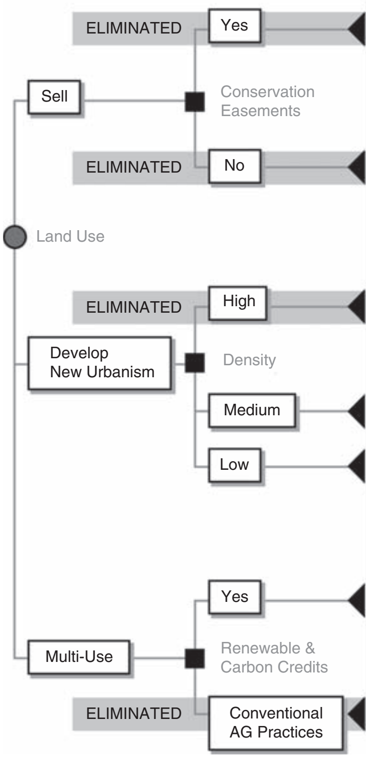
setting a comparison threshold. For example, the landowner may determine that she does not want to continue with any alternative that has less than a 50 percent qualitative value compared to the best alternative for achieving her family legacy goals. As shown in Figure 8.10, this would eliminate alternative 1.

Step 3: Elimination of Equal Objectives

After the dominated alternatives and those that fail to meet threshold conditions are eliminated, it becomes easier to determine if some objectives are essentially equal. If the alternatives satisfy a particular objective equally, that objective no longer provides meaningful information for the decision selection process. The performance of alternatives 4, 5, and 6 against the objectives is shown in Figure 8.11. The environmental objective of obtaining ecosystem integrity is satisfied approximately equally by the remaining three alternatives: medium- and low-density development using a New Urbanism model and the multi-use agriculture practice portfolio that includes activities for renewable energy and greenhouse gas carbon credits. Although there is some difference, the landowner may well decide that it is trivial considering the range of uncertainty in the scale of comparison. The performance metric after the equal objectives are eliminated is shown in Figure 8.12.

Step 4: Combination of Objectives

The next step in the analysis process is determining whether some objectives can be combined or are providing essentially redundant information for the remaining alternatives. Candidates for combination in our example include the two social



	Economic Indicators			Social Indicators		Environmental Indicators	
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Yes (ELIMINATED)	84	14	98	28	28	56	28
No (ELIMINATED)	98	28	84	14	14	14	14
High (ELIMINATED)	70	84	14	70	98	28	42
Medium	56	70	28	56	84	65	70
Low	42	42	70	42	56	60	84
Yes	14	98	42	98	70	58	98
Conventional AG Practices (ELIMINATED)	28	56	56	84	42	42	56

[1] Debilitating loss defined as a single year loss > $50,000 or total five-year loss greater than $300,000

[2] Family integrity and influenced combined

[3] Family influence as the impact of multiple generations on the social and power structures of the community

FIGURE 8.10

Qualitative threshold elimination of alternative.

objectives identified at the beginning of the decision exercise that deal with the landowner's desire to leave a legacy. The legacy objectives were captured by a qualitative measure of the extent to which the decision is expected to provide opportunity to multiple generations of the family through the ability to generate wealth or value, as well as the opportunity to have influence on the community.

At this point in the analysis, the decision maker may determine that the two objectives can be combined with no loss of meaningful decision input. The

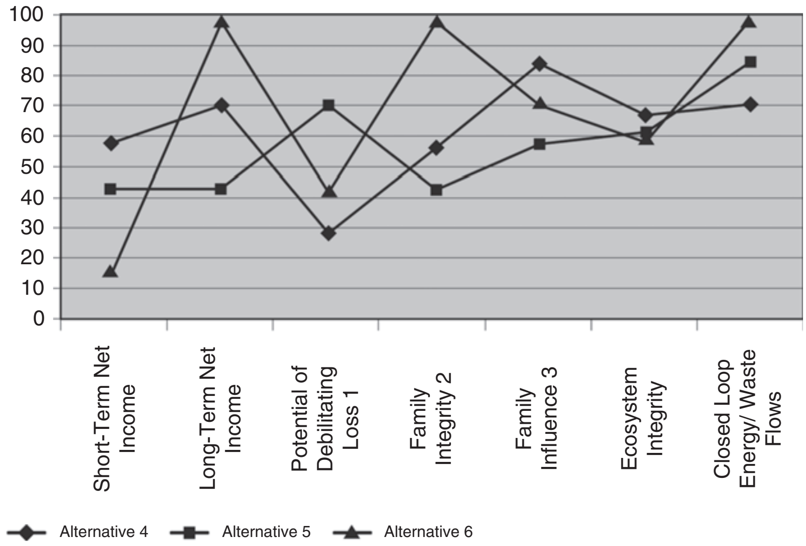


FIGURE 8.11

Elimination of equal objectives.

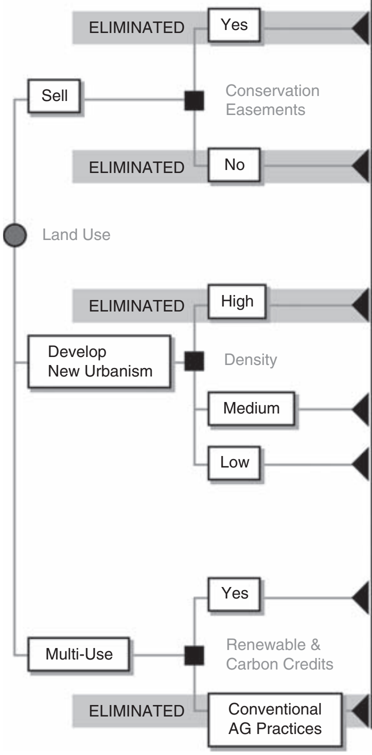
combination can be accomplished through a simple averaging of the two objectives or through the weighting of one against the other if there is some reason to value one over the other. Figure 8.13 provides the performance matrix following this step.

Step 5: Elimination of Nonforcing Objectives

As the alternatives and objectives are reduced through steps 1 through 4, it becomes simpler to determine if any objectives can be eliminated altogether. Any objective that the decision maker determines would not force him to choose between the remaining alternatives can now be removed from consideration. In our example, the landowner can eliminate the objective of avoiding debilitating negative cash flow. For our decision maker, this objective was effectively resolved by eliminating any alternative that didn't meet a threshold level of protectiveness. Although she may not like the idea of losing more money with one alternative than with another in a given year, the landowner has already accepted that there is a level of loss that is tolerable and any loss less than that is acceptable.

Step 6: Mitigation to Balance Alternatives

The first five steps constitute a screening of the alternatives and objectives to simplify the performance matrix as much as possible. In our example, the performance



		Economic Indicators			Social Indicators		Environmental Indicators	
		Short-Term Net Income	Long-Term Net Income	Potential of Debilitating Loss[1]	Family Integrity[2]	Family Influence[3]	Ecosystem Integrity	Closed Loop Energy/ Waste Flows
Sell – Conservation Easements	Yes (ELIMINATED)	84	14	98	28	28	56	28
Sell – Conservation Easements	No (ELIMINATED)	98	28	84	14	14	14	14
Develop New Urbanism – Density	High (ELIMINATED)	70	84	14	70	98	28	42
Develop New Urbanism – Density	Medium	56	70	28	56	84	65	70
Develop New Urbanism – Density	Low	42	42	70	42	56	60	84
Multi-Use – Renewable & Carbon Credits	Yes	14	98	42	98	70	58	98
Multi-Use – Renewable & Carbon Credits	Conventional AG Practices (ELIMINATED)	28	56	56	84	42	42	58

[1] Debilitating loss defined as a single year loss > $50,000 or total five-year loss greater than $300,000

[2] Family integrity and influenced combined

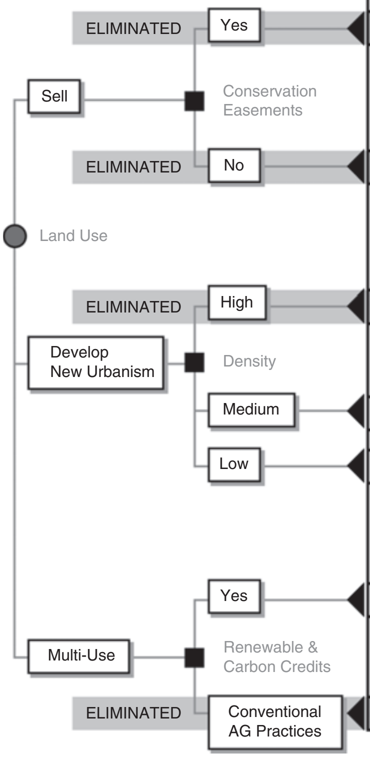
[3] Family influence as the impact of multiple generations on the social and power structures of the community

FIGURE 8.12

Performance matrix after elimination of equal objectives.

matrix has been reduced, as shown in Figure 8.14, from a grid of 49 cells to one of 12 cells, with 4 independent objectives and 3 remaining alternatives.

The next step is to revisit the performance of the alternatives, as shown in Figure 8.15. The intent at this stage is to identify any opportunity to lessen the difference between the performance of remaining alternatives to obtain a new dominated alternative. Alternative 4, medium-density development under New Urbanism concepts, is a candidate for such an assessment. It is superior to



	Economic Indicators			Social Indicators		Environmental Indicators	
	Short-Term Net Income	Long-Term Net Income	Potential of Debilitating Loss[1]			Ecosystem Integrity	Closed Loop Energy/ Waste Flows
Yes (ELIMINATED)	84	14	98	28	28	56	28
No (ELIMINATED)	98	28	84	14	14	14	14
High (ELIMINATED)	70	84	14	70	98	28	42
Medium	56	70	28	56	84	65	70
Low	42	42	70	42	56	60	84
Yes	14	98	42	98	70	58	98
Conventional AG Practices (ELIMINATED)	28	56	56	84	42	42	56

[1] Debilitating loss defined as a single year loss > $50,000 or total five-year loss greater than $300,000

[2] Family integrity and influenced combined

FIGURE 8.13

Performance matrix after combination of social indicator objectives.

alternative 5, low-density development, for each remaining objective except the environmental objective of closed energy and waste loops. We will assume that the design concept has sufficient flexibility for modifying the building or site layout to improve this metric by 15 percent. Such improvement may be accomplished through modifications that increase conservation, efficiency, and recycling without materially affecting the near- or long-term expected cash flow. With such a change, alternative 4 dominates alternative 5. Now there are only two alternatives, which can be compared against four independent objectives.

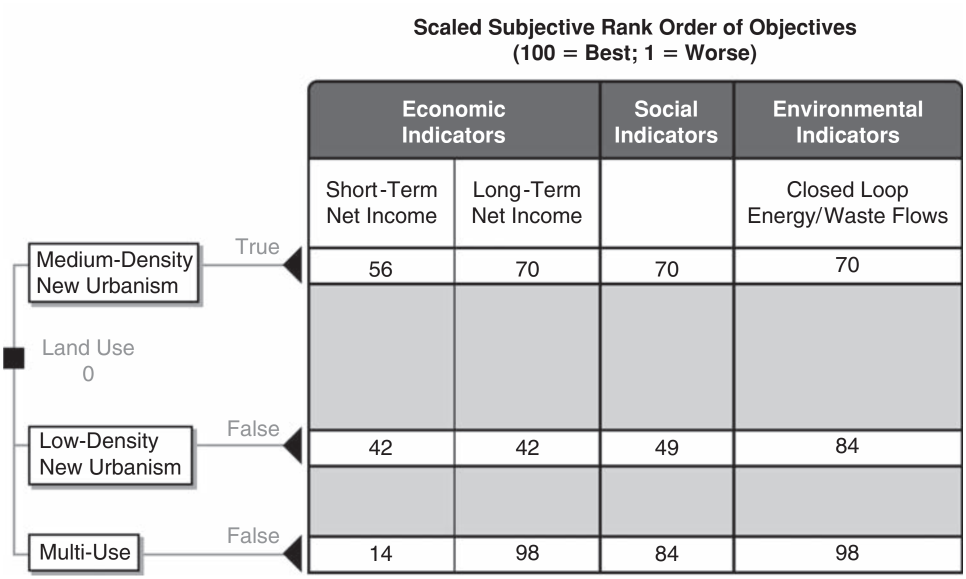


FIGURE 8.14

Revised performance matrix after screening of alternatives and objectives.

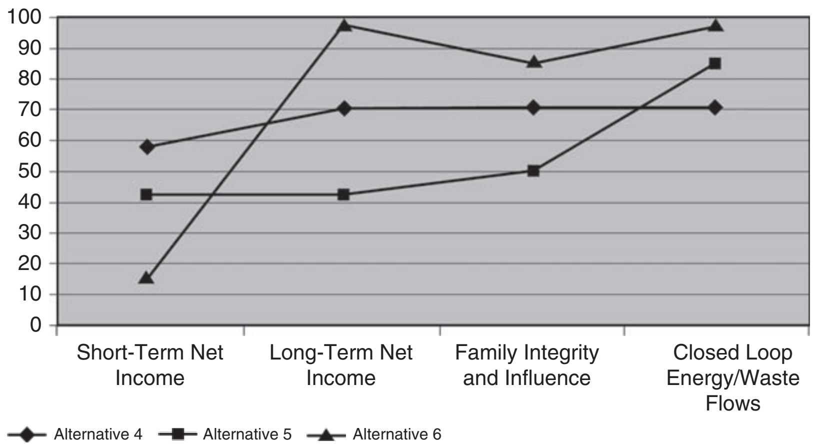


FIGURE 8.15

Revised examination of alternative performance after screening of alternatives and objectives.

Step 7: Trade-Offs

Once the screening and mitigation assessment steps have been completed, the decision-making team must determine whether trade-offs among different criteria are acceptable. Can good performance with respect to one objective appropriately compensate for the weaker performance of another? Most decision settings implicitly acknowledge the need for such trade-offs, which can be assessed in an explicit and well-documented manner when the decision makers use a performance matrix. This step is much easier when the first six steps have been implemented and the number of alternatives and objectives has been reduced.

In our example, the compensatory opportunity lies in rebalancing long- and short-term goals. As can be seen in Figure 8.16, alternative 6, multi-use agriculture, provides significant advantages for the long-term social and environmental objectives as well as for the objectives of expected long-term net economic return. However, the landowner pays a heavy price in the short-term net return. The difference in performance of the two alternatives against the short- and long-term objectives is made even more significant by the relative time value of short-term advantages. A return in the near term has greater value than a return in the future for two reasons: the time value of money and the increased uncertainty as the time horizon expands.

An example of a trade-off exercise is shown in Figure 8.17. The obvious trade-off in this case is to lessen the near-term investment in long-term benefits to bring the cash flow over the two time horizons more in line with each other. In the first step, the landowner may reduce her up-front investment in a medium-density New Urbanism development. This will improve near-term cash flow at the expense of long-term cash flow. In the second step she can scale back some elements of the environmental objective to improve her near-term cash position.

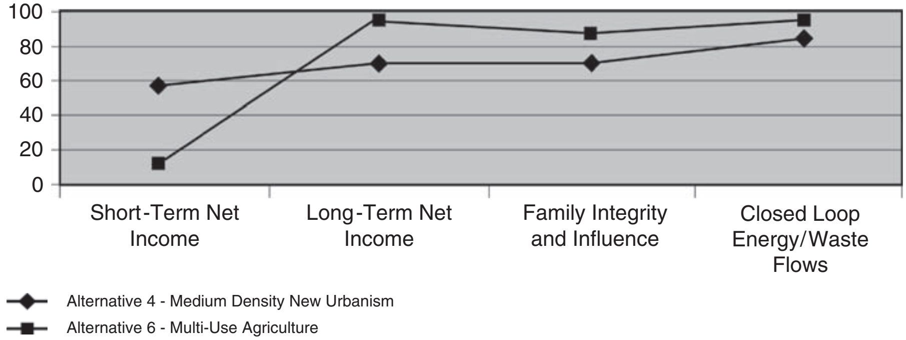


FIGURE 8.16

Final result of all screening.

Example of Trade-Offs in Performance Matrix

Trade-Off Table (a)

	Alternative 4 Medium-Density New Urbanism	Alternative 6 Multi-Use Agriculture
Short-Term Net Income	56	14
Long-Term Net Income	70	98
Family Integrity and Influence	70	84
Closed-Loop Energy/Waste Flows	84	98

Trade-Off Table (b)

	Alternative 4 Medium-Density New Urbanism	Alternative 6 Multi-Use Agriculture
Short-Term Net Income	56	14 + 20 = 34
Long-Term Net Income	70	98 − 20 = 78
Family Integrity and Influence	70	84
Closed-Loop Energy/Waste Flows	84	98

Trade-Off Table (c)

	Alternative 4 Medium-Density New Urbanism	Alternative 6 Multi-Use Agriculture
Short-Term Net Income	56	34 + 14 = 48
Long-Term Net Income	70	70
Family Integrity and Influence	70	84
Closed-Loop Energy/Waste Flows	84	98 − 14 = 84

FIGURE 8.17

Example of trade-off in performance matrix.

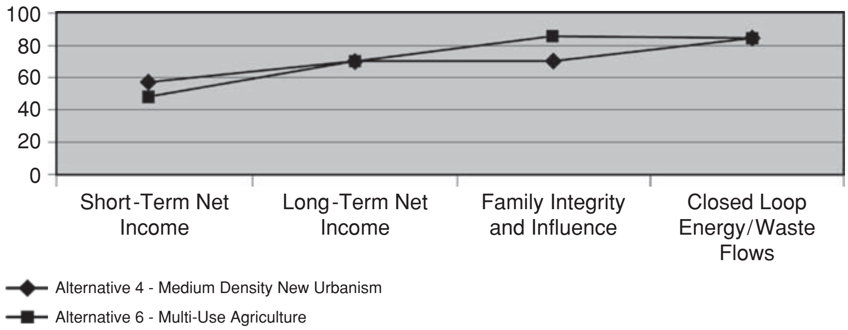


FIGURE 8.18

Graphical representation of final performance matrix.

Step 8: Choosing Through Clarification of Values

The final step is identification of the relative importance of the differential between remaining alternatives with respect to the remaining objectives in the performance matrix. The graphical presentation of the final performance matrix for our landowner is shown in Figure 8.18. Two of the objectives have now become nonissues. In the final analysis, the landowner has reduced her choices to two alternatives that are quite different but quite similar with respect to her objectives. She now has to choose which of the two objectives is most important: short-term cash flow or her family's legacy. She can accomplish her objectives with either of the remaining two alternatives, but one has a slight advantage in terms of cash flow and the other a slight advantage in terms of the legacy she leaves for her family.

A point is reached in any decision setting in which the analytical and process tools as discussed here reach their limit. The tools can carry the decision makers to a place where the final working-through of values and choices is simplified, but in the end individual values will be the final arbitrator.

8.7 PERFORMANCE MATRIX AGGREGATION

The aggregation approach establishes a relative value or importance of the objectives through a multi-criteria aggregation procedure. Various inter-criteria parameters can be used to create a single numerical value that aggregates all of the performance metrics into a single numerical value attached to each alternative. These parameters may consist of weighting each of the objectives in terms of importance using scaling constants, veto or elimination criteria, aspiration levels, or rejection levels. They allow the decision maker to identify the relative importance placed on the objectives and their performance metrics.

The logic of the aggregation, and the documentation of that logic, is of the utmost importance. The value relationships of the objectives in all but a very few instances will be subjective but should still be logical and analytically rigorous. All aggregation approaches address the relative importance of the different objectives explicitly and require judgment to define this relative importance. Generally, there is an explicit relative weighting system for the different objectives, the purpose of which is to deal with large amounts of complex information consistently. The aggregation techniques, especially if the aggregation uses fuzzy sets for the generation of a single variable, can provide a wealth of information that captures expected values and uncertainty together.

Consider our landowner. As a simple first cut, any alternatives that fail to meet a threshold requirement for one of more objectives can be eliminated. As discussed in the previous section, alternative 3 was eliminated because of the unacceptable probability of producing a debilitating negative cash flow. In the aggregation approach, the remaining alternatives can be left in the assessment. The next task is to generate an algorithm for combining performance values for each objective for each alternative into a single value or, at least, a single profile.

There is no one guideline for combining the multiple objectives into a single algorithm. The one that comes closest to universal acceptance is based on multiattribute utility theory from the work of Von Neumann and Morgenstern (1947) and Savage (1954). However, this theory has serious limitations in practical application, although it does provide helpful theoretical insight. The work of Keeney and Raiffa (1976) is more useful in the evaluation of multiple objectives in practice.

Keeney and Raiffa's approach consists of estimating the parameters in a mathematical function that allows the development of a single number index to express the decision maker's overall valuation of an alternative in terms of its performance on each of the objectives. This approach is complex and inaccessible to the general practitioner, scientist, or policy maker. It is seldom practical except on major projects with sufficient funding, time for implementation, and extensive and deep commitment of time, energy, and intellectual engagement by the decision-making team. Keeney and Raiffa's model takes uncertainty formally into account by building it directly into the decision support models. It also allows attributes to interact in other than a simple, additive, and/or weighted fashion.

Although the Keeney and Raiffa robustness model may be valuable in some settings, in practice, trying to include such a robust set of variables can lead to paralysis due to complexity. In most circumstances, a simplified approach is appropriate. The intent is to achieve transparent and effective decision making that accurately captures the qualitative differences in values, judgment, and experience. The intent is not to capture them in a mathematically rigorous model. The simpler approach of linear and/or weighted modeling makes the technique available to a wider range of users and for a larger set of problem types.

A simple linear additive evaluation multiplies the alternatives score on each objective by the weight of that objective and then adds the weighted scores together. Models of this type have a well-established record of providing robust and effective support to decision makers working on a range of problems and in various circumstances.

An example weighting scheme for the decision setting discussed in the previous section is shown in Figure 8.19. The landowner or her group of decision makers collectively determine the relative weight they are comfortable with among the three classes of objectives: economic, social (or family), and environmental. This may be as simple as an even distribution, or it may be determined through various polling or interview techniques that determine the importance placed on each of the three areas of performance. Next, the distribution of importance among objectives within the same class (i.e., economic, social, and environmental) can be determined.

The "swing weighting" method is the most common technique for determining the types of weights just described. It develops weights based on a comparison of how the swing from 0 to 100 on one preference scale compares to the 0 to 100 swing on another scale. Decision analysts take into account the difference between the least and most preferred options and how important that difference seems to them personally. For example, assume there is initially the choice of forest product development, commodity agricultural food production, and organic food production. Within each choice there are three to five choices for how the particular

Example Weighting of Objectives

	Weight between Classes of Objectives	Weight within Classes of Objectives	Weight
Short-Term Net Income	33.0%	45.0%	14.9%
Long-Term Net Income		55.0%	18.2%
Family Integrity 2	40.0%	65.0%	26.0%
Family Integrity 3		35.0%	14.0%
Ecosystem Integrity	27.0%	40.0%	10.8%
Closed Loop Energy/Waste Flows		60.0%	16.2%
			100.0%

FIGURE 8.19

Example weighting scheme for aggregation of objectives.

practice will be implemented. Within each of these choices, the short-term costs for developing the product line vary by less than the landowner's comfortable cash flow capacity. In this case, an objective of short-term cash flow reduction may not have a heavy weight because it is not a critical driver. That objective receives a low weight because of the difference between the highest and lowest near-term cash flows.

Often, there is a crucial difference between measured performance and the value of that performance in a specific decision context. Performance improvements may be real but not necessarily useful or not a critical driver in the decision setting. A marginal improvement in performance may not contribute to a corresponding increment in perceived value. The *weight* of a specific objective is a combination of both the range of differences between the alternatives and how much those differences matter.

As described in the *Multi-Criteria Analysis Manual* developed by Spackman and colleagues (2000), the swing weighting method can be implemented by a decision team with the "nominal-group technique." First, the objective with the biggest swing in preference from 0 to 100 is identified. If there are many objectives, a paired-comparison process in which objectives are compared two at a time for their preference swings may be applied. With this method the objective with the bigger swing is retained to compare to the next objective. The one criterion emerging from this process that shows the largest swing in preference becomes the standard to which the others are compared.

The *Multi-Criteria Analysis Manual* describes a four-step process:

1. Each objective is examined individually, and all members of the decision-making team are asked to identify, without discussion, a weight that reflects their individual judgments of its swing in preference compared to the standard. If the objective is judged to represent half the swing in value as that of the standard, for example, it should be assigned a weight of 50.

2. Participants reveal their judged weights to the group, and the results are recorded as a frequency distribution.

3. Participants who gave extreme weights, high and low, are asked to explain their reasons, and a general group discussion follows.

4. Having heard the discussion, a subset of participants makes the final determination of the weight for the criterion.

As identified by Spackman, this approach allows for a determination of weights informed by collective wisdom, starting from knowledge of each participant's position prior to any influence from the others. The process of deriving weights is as important as the weights themselves and must be documented so it is clear and unambiguous.

The results of the aggregation in this example are shown in Figures 8.20 and 8.21. An additional level of analysis can be achieved by capturing the range of

Weighted Alternative Comparison						
Alternatives	1	2	4	5	6	7
Short-Term Net Income	84	98	56	42	14	28
Long-Term Net Income	14	28	70	42	98	56
Family Integrity 2	28	14	56	42	98	84
Family Integrity 3	28	14	84	56	70	42
Ecosystem Integrity	56	14	98	84	70	42
Closed Loop Energy/Waste Flows	28	14	70	84	98	56
	36.8	**29.0**	**69.3**	**55.3**	**78.6**	**55.7**

FIGURE 8.20

Example alternative weights.

Summary of Aggregation MCDA		
Alternative 6	Multi-Use Agriculture	78.6
Alternative 4	Medium Density New Urbanism	69.3
Alternative 7	Traditional Aggregation Practices	55.7
Alternative 5	Low Density New Urbanism	55.3
Alternative 1	Free Simple Sale With Conservation Easement	36.8
Alternative 2	Free Simple Sale	29.0

FIGURE 8.21

Summary of aggregated alternative weights.

Input Variables as Distributions of Values				
	Max.	**Average**	**Min.**	**Agg.**
Family Influence	50.0%	50.0%	30.0%	50.0%
Relative Weight between Economic and Environmental	60.0%	55.0%	50.0%	55.0%
Long-Term versus Shot-Term Economic	60.0%	55.0%	50.0%	55.0%
Family Integrity versus Family Influence	70.0%	65.0%	60.0%	65.0%
Ecosystem Integrity versus Closed Loop Energy/Waste Flows	50.0%	40.0%	30.0%	40.0%

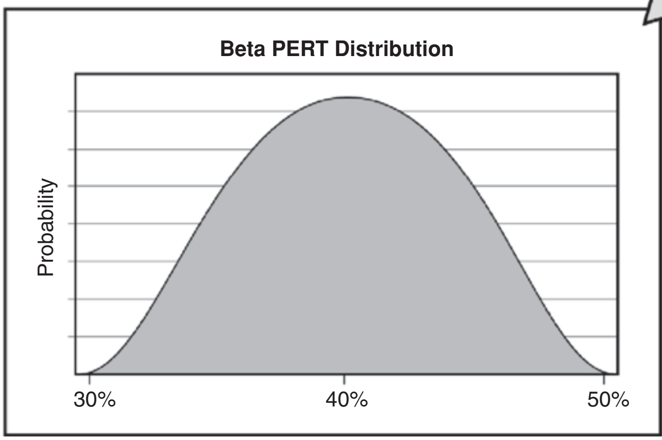


FIGURE 8.22

Variable inputs for aggregated alternative weights.

potential weighting preferences. For example, instead of picking a single weighting value as described in step 4, a distribution of values may be chosen. This distribution may be derived from the range of values identified in step 2 or from the step 3 discussion in which the range is modified to eliminate obvious outliers. An example of the variables that might result from such an approach is shown in Figure 8.23.

Using the variable input approach allows decision makers to more readily assess the sensitivity of their assumptions. An example of the output from the variable assessment of the aggregated value for each of the alternatives is shown in Figure 8.23. As shown, the results are quite robust in that the conclusions from the aggregation do not change within the range of possible inputs for the assessment.

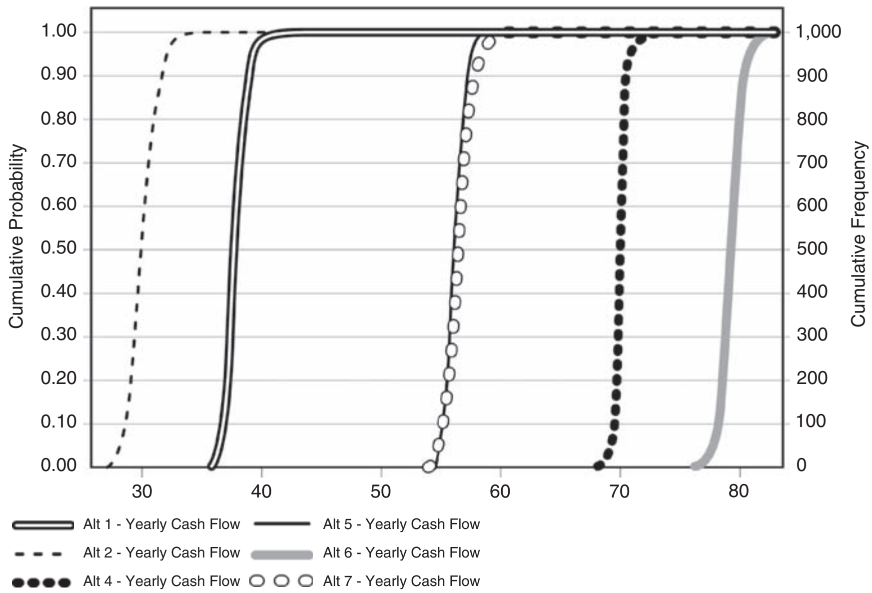


FIGURE 8.23

Variable aggregated output for each alternative.

8.8 ADVANTAGES OF MCDA OVER INFORMAL JUDGMENT

As described by Spackman and colleagues (2000), MCDA has many advantages over informal judgment unsupported by analysis. These are as follows:

- It is open and explicit.
- The choice of objectives and criteria that any decision-making group may make is open to analysis and can change as information and values are disclosed.
- Scores and weights, when used, are explicit and developed according to established, defined, and documented techniques.
- Performance metrics, scores, and weights can be cross-referenced to other sources of information on relative values.
- Performance metrics can draw on the experience and expertise of discipline specialists.
- The process itself develops a means of communication within the decision-making body, the immediate stakeholder group, and the wider community.
- It provides a transparent audit trail.

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CHAPTER

9 Developing Performance Metrics

William L. Hall

9.1 INTRODUCTION

The previous chapters addressed the concepts of developing a decision context, creating an analysis framework through influence diagrams and decision trees, and using performance metrics for analyzing the consequences of various alternatives. In this chapter we will examine in more detail the tools and approaches for generating an analytical model of the decision setting.

The purpose of an analytical model for a decision context is to provide a scaled measure of the range of possible outcomes based on judgment, values, and experience. The outcome of a particular alternative with respect to a particular objective cannot be measured before the fact. It may not be possible to accurately measure even after the selected alternative has been implemented. It is one thing to establish a performance metric; it is quite another to predict how well an alternative might satisfy it or to determine how well it actually does satisfy it.

Even an economic metric as seemingly simple as return on investment or growth in stock value can be maddeningly imprecise or subject to gaming. The recurrence of economic bubbles demonstrates the inaccuracies of supposedly simple measures of success. This has been observed from the run-up in tulip bulb values in the 16th century to the real estate boom of the early 21st century, fueled by exotic financial mechanisms for risk transfer. Measures of success, or performance metrics, were being met, and masters of the decision settings were rewarded accordingly. But, in the end, the performance metrics were either poorly designed or poorly insulated against gaming.

It is not difficult to recognize, at least at some intellectual level, that we do not control the future. Decision making is further complicated, though, by the fact that even our understanding of the present is a product less of reality than of our own particular package of biases and heuristics. We must predict the consequences of our decisions in the future based on the trajectory of events in the past. And even here we encounter potentially debilitating limitations from incomplete and imperfect—if not intentionally misleading—information, which is invariably skewed by personal agendas.

DOI: 10.1016/B978-1-85617-797-9.00009-5

In the physical realm it is possible to predict with certainty the response to or the result of certain physical, chemical, and biological actions. A ball dropped from a known height from the Leaning Tower of Pisa will fall at a defined rate of acceleration and strike the earth at a known velocity. However, once the ball interacts with the earth, a series of unknowns comes into play. The height of bounce will be a function of the density of the ground the ball encounters and the ball's physical characteristics. Those characteristics will be a function of the ball's temperature and density and the temperature and density of the surrounding air. The angle of bounce will be a function of the angle of impact as determined by ambient wind vectors and the slope of the particular patch of ground encountered. The same variables come into play with each subsequent bounce of the ball.

Our predictions about the ball's ultimate trajectory can range from pure experience, arising from a lifetime of dropping balls from the Leaning Tower of Pisa, to a blended probabilistic/deterministic approach that allows us to capture knowledge of how certain actions and reactions follow definable rules, even if the input variables are unknown or poorly understood.

The analytical approach and tools detailed in the following sections provide mathematically scaled performance metrics built from mathematically scaled uncertainties. A critical consideration is that these metrics do not represent the measurement of a physical thing, like the weight of an apple or the number of dollars in a bank account. Rather, they represent a composite mathematical distribution of a decision team's judgment of an alternative's probable success in achieving an objective, relative to other available alternatives.

Applying the tools discussed here is neither easy nor quick, but it will have a huge payoff if the decision team is able and willing to engage in the rigorous thinking and interaction required.

9.2 DEFINING PERFORMANCE METRICS

This section provides a step-by-step description of a procedure for developing scaled performance metrics. Scaled performance metrics replace the more common and traditional advocacy-based approach to decision making. Advocacy-based decision making, which currently dominates the sustainability debate, allows individuals and special interest groups to maintain hidden agendas. It permits, and often rewards, ignorance, tunnel vision, and domination by narrow self-interest. Employing scaled performance metrics is a powerful way to prevent the loudest and most influential advocate from dominating a land or resource management decision setting.

9.2.1 Performance Metric Characteristics

A scaled performance metric will prevent many of the organizational and individual problems of an advocacy-based approach to decision consequence analysis. In addition, it will provide a means for uncovering the influence of psychological traps (discussed in Chapter 4). Defining the performance metrics themselves requires a combination art, science, and engineering. A functional performance metric for a given objective should have the following characteristics:

- It provides a measure that a decision team agrees is a functional surrogate for the team's collective understanding of the objective.
- It provides a clear and unbiased comparison of alternatives.
- It is amenable to disaggregation of underlying components to simplify the assessment of uncertainty.
- It is composed of scalable characteristics, even if those characteristics can only be scaled qualitatively.
- It provides a measure of threshold requirements.

9.2.2 Economic Performance Metrics

Economic performance metrics are the simplest to understand and the most amenable to quantification and relatively straightforward algorithms. In the rezoning example in Chapter 8, the landowner was primarily concerned with net return, total amount of profit over various time periods, and cash flow. Other measures might be return on investment, payback period, growth in equity, and diversification of income stream, to name a few. All of these metrics match the five characteristics just listed.

9.2.3 Monetized Environmental Performance Metrics

Defining the noneconomic performance metrics for, say, the social and environmental objectives of Chapter 8 is more challenging. One approach is to monetize these objectives to create a performance metric denominated in dollars. There is still the need to break each objective into component functions and convert those functions into dollar values based on the services they provide.

Examples of ecological services that can be directly monetized include air purification, greenhouse gas mitigation, water storage through groundwater recharge, water purification through natural vegetation or wetlands, flood control, decomposition of waste streams, pollination of crops, and ambient temperature buffering. The ease of monetizing these services comes from the relatively limited number of steps between the ecological service and its impact on human infrastructure.

An example is the impact of the conversion of forest land to impervious surfaces. Over 50 percent of rain that falls on forest land will filter into the ground, as illustrated in Figure 9.1 (Marsh, 1997). This infiltrating water can, over time, migrate into adjacent streams and rivers as interflow (lateral movement of water through the ground, in places where features of soil or bedrock prevent further vertical migration), or it can travel vertically to recharge local aquifers. When forest land is converted to impervious surfaces, the ratio of infiltrating water to water

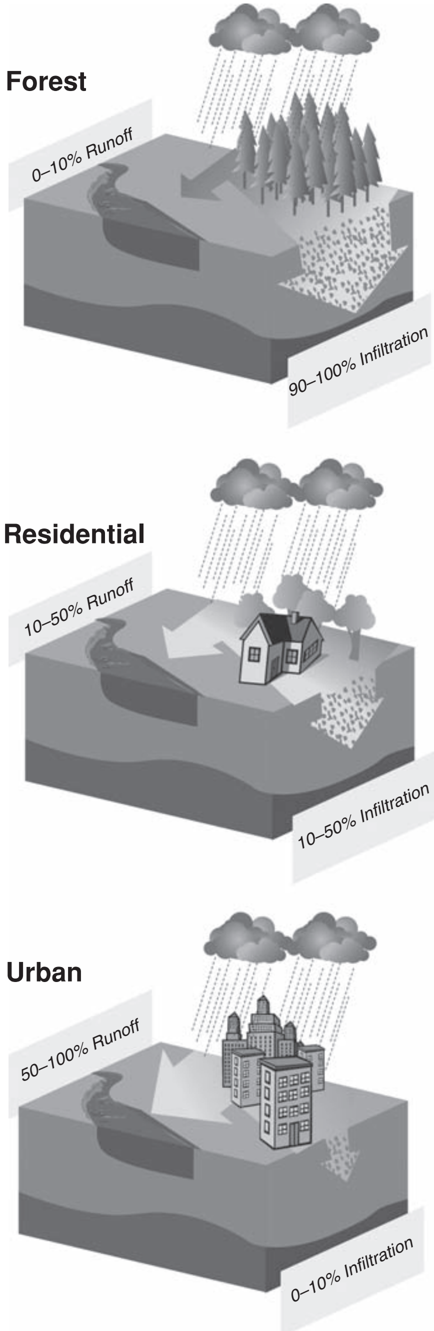


FIGURE 9.1

Impact of impervious surfaces.

runoff immediately begins to decrease (Figure 9.2). As the infiltration decreases, the amount of vertical flow and interflow also decreases.

A decrease in rainfall infiltration has a direct economic impact on any region that has dry and rainy season variability in which water supply for potable uses, irrigation, or manufacturing must be provided entirely or in part from storage during some months of the year. The loss of natural water storage—in the groundwater or in streams—has direct economic consequences. For example, an average cost for replacing natural storage with man-made reservoirs is shown in Figure 9.3. This information is drawn from the author's experience with reservoir construction in the Piedmont region of the southeastern United States. Because the best reservoir locations have long since been developed, the unit cost for providing an acre-foot of storage is quite high.

In the example shown in Figure 9.3, the unit capital cost for each acre-foot of reservoir storage is almost $1,300. Paving an acre of land with no mitigation of the increase in runoff can eliminate from 1.75 to 2 acre-feet of natural storage. This translates into a societal cost of between $2,000 and $2,500 for each acre of paved property that has no mitigation (infiltration ponds, pervious paving, etc.).

Water storage from upland forests or wetlands is one of the more straightforward ecological services that can be monetized to obtain performance metrics. Other ecological services provided by forest land can be addressed with varying levels of

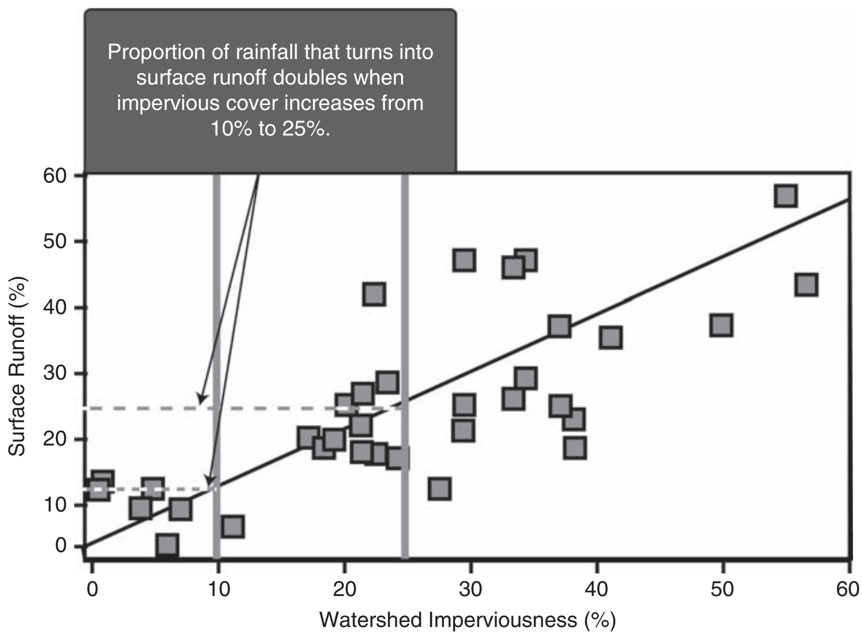


FIGURE 9.2

Decreasing infiltration in proportion to increases in impervious surfaces.

Representative Costs for Providing Reservoir Storage in Atlanta Metropolitan Area				
Description	**Units**	**Unit Cost per Acre**	**Quantity**	**Total**
Land Acquisition	Acres	$20,000	1,500.00	$30,000,000
Design	Lump Sum	$2,000,000	1.00	$2,000,000
Land Cleaning	Acres	$1,500	1,000.00	$1,500,000
Construction—90-foot-high roller compacted dam	Lump Sum	$17,500,000	1.00	$17,500,000
Legal/regulatory/permitting	Lump Sum	$750,000	1.00	$750,000
			Total	**$51,000,000**
	Yearly Operation/ Maintenance Cost			**$750,000**

Unit Cost for Providing an Acre-Foot of Storage	
Usable average storage pool (ft)	40
Acreage	1,000
Acre-ft of storage	40,000
Capital cost per acre-foot of storage	$1,275
Yearly operation/maintenance cost per acre-foot of sorage	$18.75

Impact of Impervious Surface	
Yearly rainfall in north Georgia (inches)	50
Natural infiltration (inches)	25
Natural storage per acre (acre-foot)	2.08
Infiltration after pavement (inches)	3
Storage per acre after pavement (acre-ft)	0.25
Loss of storage	1.83
Replacement cost of lost storage per acre	$2,337.50
Yearly cost per acre of lost storage	$34.38

FIGURE 9.3

Economic impact of impervious surface due to loss of storage.

accuracy. For example, vegetation provides services for moderating ambient air temperatures and for removing impurities from soil and water.

An example of the indirect ambient economic impact of conversion of unpaved land to paved land can be seen in the data in Figures 9.4 through 9.7. Figures 9.4 through 9.6 show the increase in impervious area over the Atlanta metropolitan

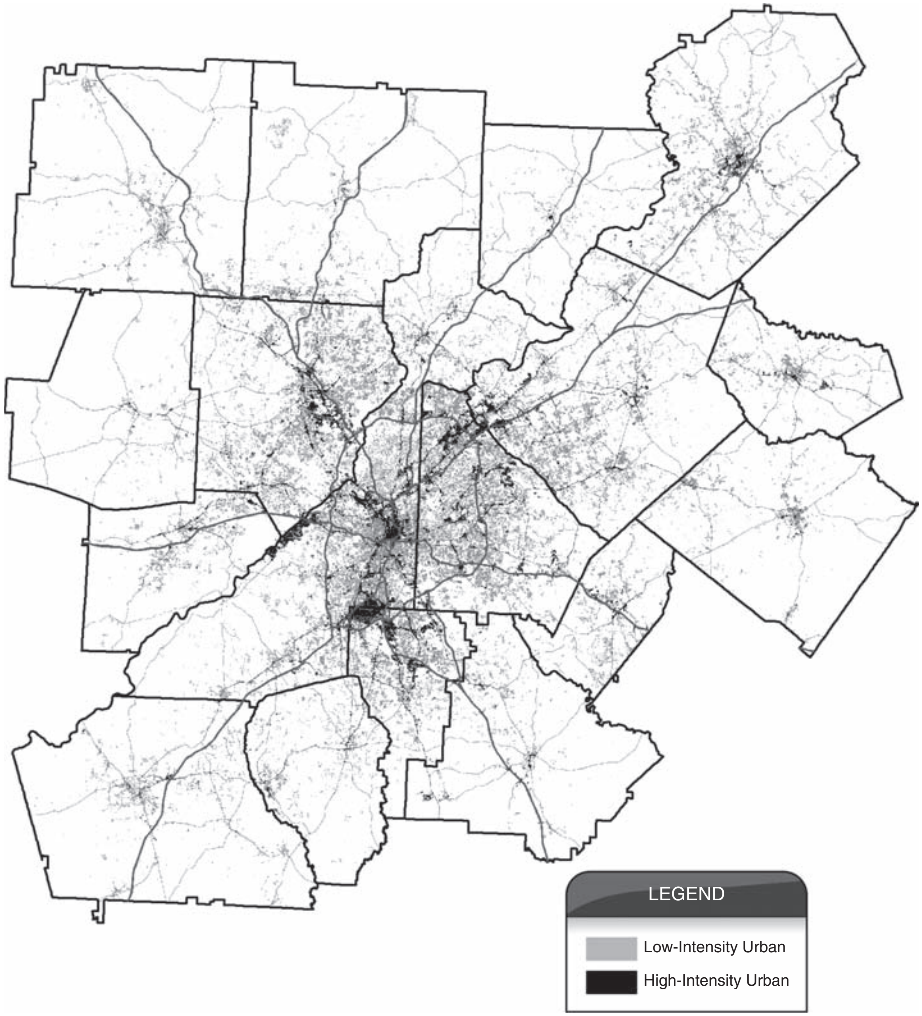


FIGURE 9.4

Metro Atlanta area impervious cover map, 1974.

area from 1974 to 2005. This increase has had a direct impact on summer temperatures, creating a heat island effect because impervious surfaces absorb and retain a greater amount of heat (in addition to the heat created by buildings and human activities) than areas covered with vegetation or trees. The direct impact of the heat island effect can be measured: temperature differentials between dense commercial centers in the Atlanta metropolitan region and the surrounding countryside can exceed 10 degrees Fahrenheit (Figure 9.7; see page 176).

An additional consequence of the heat island effect and the loss of tree canopy is changing rainfall patterns. The absence of any effective performance metric for

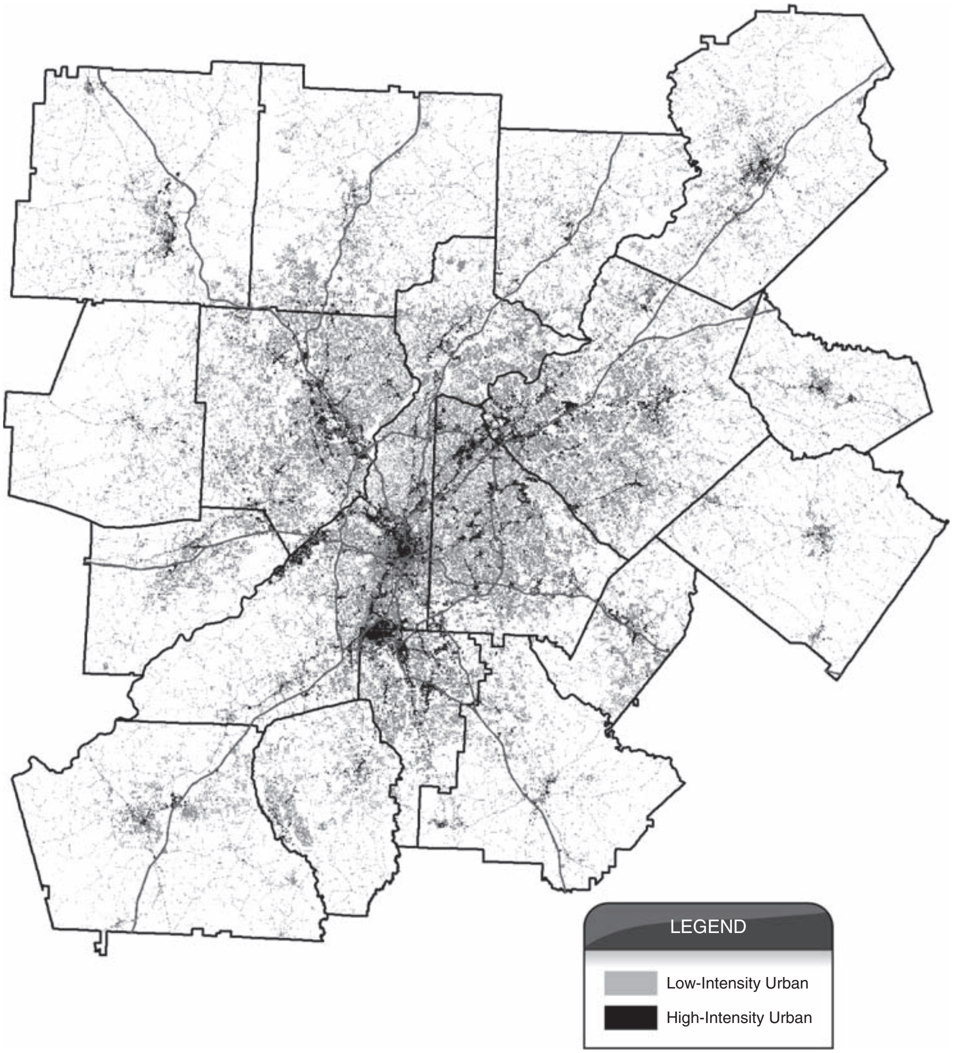


FIGURE 9.5

Metro Atlanta area impervious cover map, 1991.

ecological services can allow self-reinforcing (positive) feedback loops that are invisible until a threshold of pain is reached. Figure 9.8 demonstrates the change in average rainfall measured over the Atlanta metro area since the 1960s (see page 177). The potential decrease in rainfall, increased heat, and loss of natural storage all converge to decrease the capacity of this particular region to maintain existing quality of life. Yet under traditional economic performance metrics, at least until the real estate bubble burst in 2008, Atlanta was performing well.

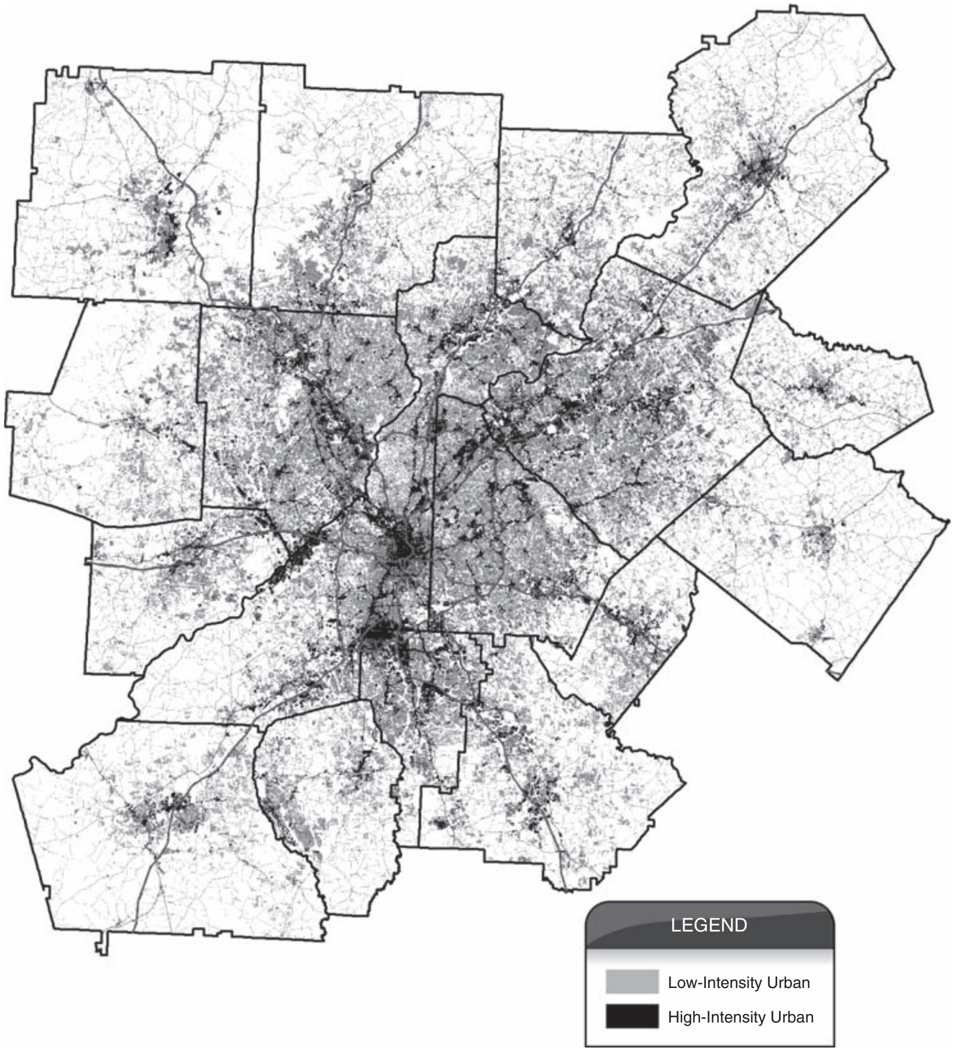


FIGURE 9.6

Metro Atlanta area impervious cover map, 2005.

However, those metrics—population growth and number of jobs—were incomplete and missed significant warning signals that perhaps the region was exploiting its future.

There are several relatively complex steps in making the connection between development patterns and their economic impact with respect to services such as climate moderation. An influence diagram linking input variables and a monetized performance metric for climate moderation is shown in Figure 9.9 on page 178. The

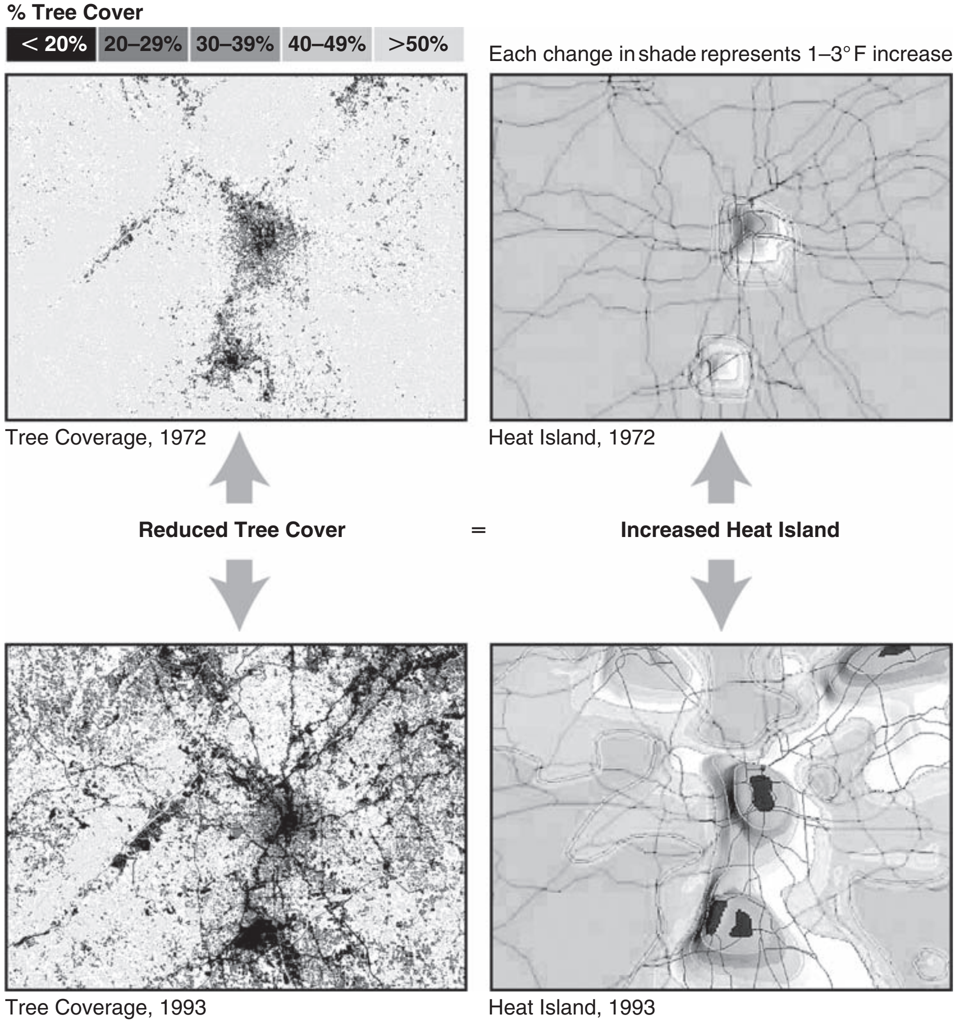


FIGURE 9.7

Temperature and water quality moderating impact of vegetation. *Source*: Figures from American Forest, 2002.

initial variables are the relationships between a particular land surface conversion and what is or will be happening around it. The extent of impervious surface within various zones of the development will affect the attenuation of any development-specific temperature alterations.

This information, coupled with potential mitigation measures, will provide an estimate of the potential incremental summer and winter temperature changes

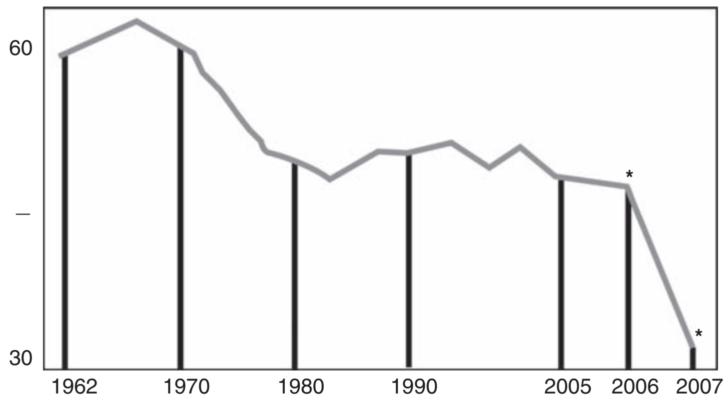


FIGURE 9.8

Ten-year moving average rainfall (inches). Bolton rainfall gauge, Atlanta (collected by National Oceanic and Atmospheric Administration).

and durations. It requires further conversion to estimate its impact on direct energy costs and ancillary costs associated with changes in available summer rainfall and water use demands. Although uncertainty is associated with each of these inputs, it is still possible to obtain reasonable ranges for the costs being offloaded to society, now or in the future. With the Monte Carlo techniques discussed in Chapter 10, the range of uncertainty for each variable can be captured to produce an overall profile of a monetized performance metric for ecological services.

Another example of the importance of appropriate performance metrics for ecological services is the management of stormwater quantity. Currently the near universal performance metric for stormwater control is maintaining post-construction peak flows at or below preconstruction levels. However, as shown schematically in Figure 9.10, this metric is not effective in actually preserving riverine systems. Aside from the fact that it completely misses the vital service of natural water storage, it fails even in terms of flow rates. Stormwater control may reduce short-lived peak flows, but it lengthens the duration of high flows that govern the equilibrium dimensions, which in turn changes the equilibrium characteristics and dimensions of the receiving streams. This can be seen in the schematic shown in Figure 9.11, in which a stream's dimensions will adjust to accommodate changes in erosion forces (see page 180). These forces are a function of flow rate and duration and are cumulative down through a stream.

A performance metric that focuses on one limited property may decrease peak flows exiting the property, but because of the extended duration of high flows, it may, and probably will, increase the peak flow and its duration in the receiving stream. The impact of this can be seen in Figures 9.12 through 9.14 (see pages 181–183). Figure 9.12 shows two neighboring streams and the percent of impervious cover in the watershed of each. Figure 9.13 shows the channel of creek A,

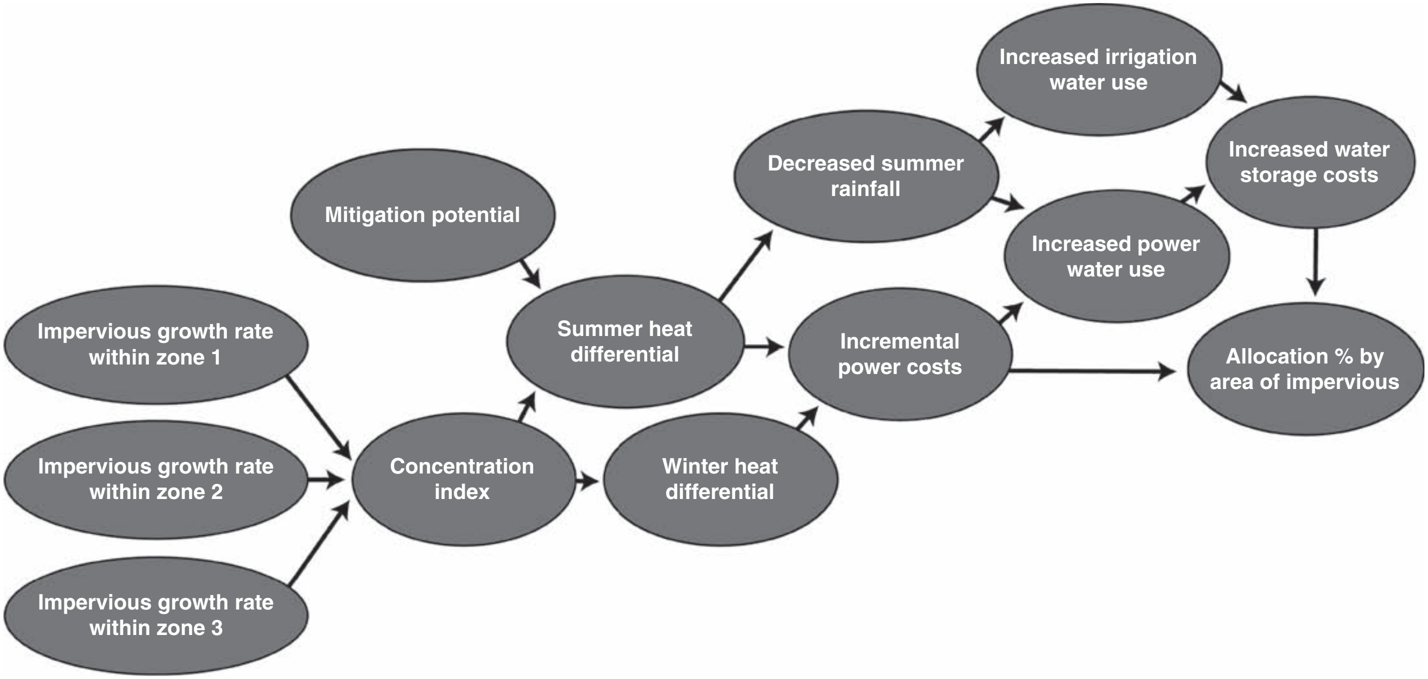


FIGURE 9.9

Input variables affecting performance metric of ambient moderation.

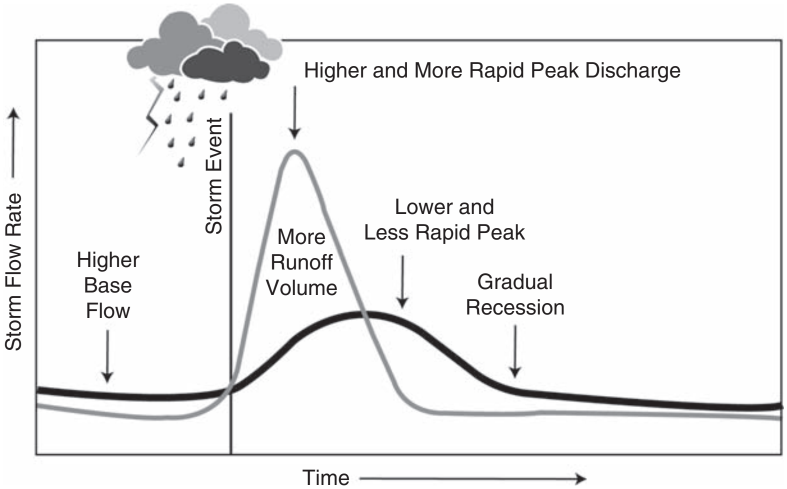


FIGURE 9.10

Peak discharge controls have the unintended effect of increasing erosion by increasing the duration of high flows into the creek.

which has only 5 percent impervious surfaces in its watershed; Figure 9.14 shows the deep downcutting and widening that has occurred in creek B, which has a watershed consisting of 19 percent impervious surfaces.

The characteristics of land use alterations that can be monetized as performance metrics are summarized in Figure 9.15 (see page 184). Monetization of an ecological service into a performance metric, even if the cost is not internalized to the property owner, at least provides a way to rationalize a decision setting involving either policy or land use. It is certainly an option for a community, city, county, state, or federal government to subsidize more sustainable land development patterns by spreading the costs of replacing ecological services across a broad spectrum of taxpayers. Without metrics for ecological services, there are limited to no opportunities for even making a decision regarding their importance.

9.2.4 Nonmonetized Environmental Performance Metrics

Some ecological services are difficult to monetize because of the vague connection between a service and its ultimate impact on human infrastructure. Examples are biodiversity, open space, aesthetically pleasing landscapes or view sheds, and wilderness. The products and processes of such goods and services are complex, they occur over long periods of time, and they do not translate easily into readily agreed on valuation.

Aside from the fact that some objectives in the environmental (and social) realm are difficult to monetize, monetization itself is an incomplete performance metric,

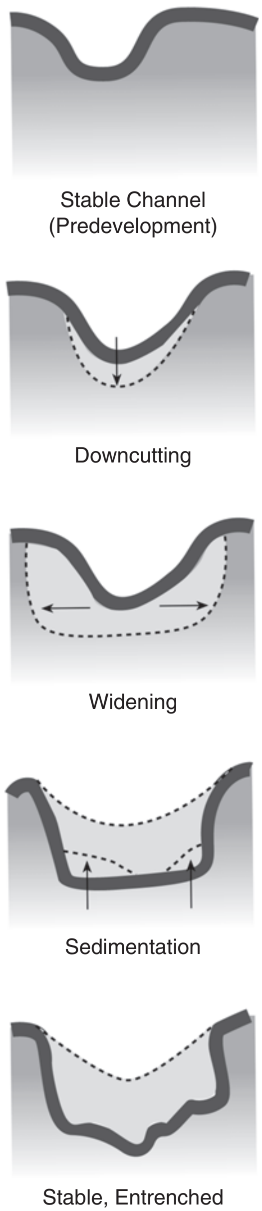


FIGURE 9.11

The effect of watershed imperviousness on the structure of a stream.

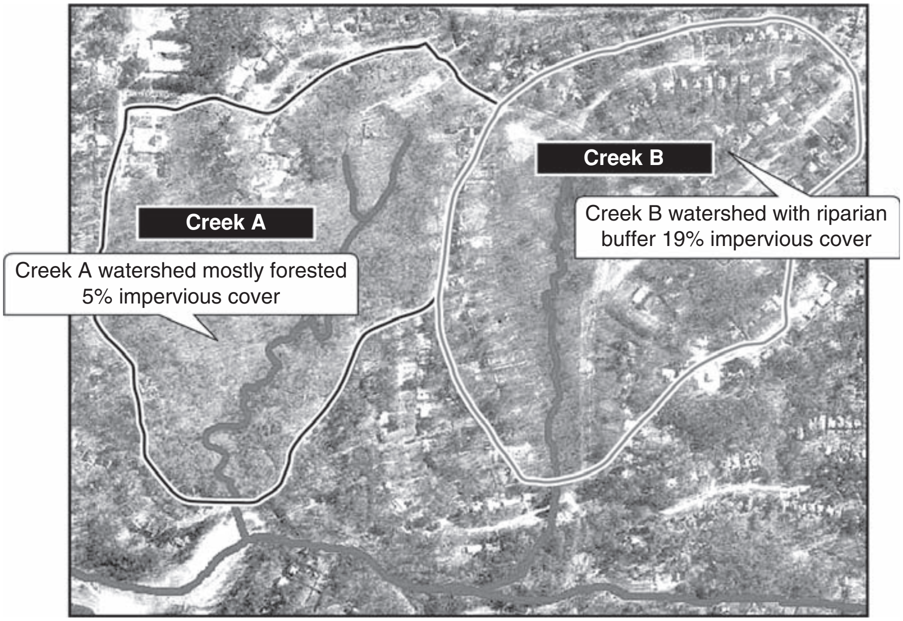


FIGURE 9.12

Impact of threshold conditions.

or at least incomplete when used alone. It fails one of the required performance metric characteristics described earlier: It is incapable of identifying threshold conditions. Someone is always willing to pay to have the trophy head of the last Siberian tiger. What is the marginal cost or value of the straw that breaks the proverbial camel's back? The monetization performance metric does not provide a ready means to address the marginal value or cost of the next lost acre of wetland or the next mile of stream that loses its healthy biodiversity.

The impact of threshold conditions is demonstrated in Figures 9.16 and 9.17 (see page 185). Both figures show that there is a level of development within a given watershed that will cause the natural systems to begin collapsing. Complementary performance metrics that act in conjunction with the monetized performance metrics are appropriate in this type of situation.

Take, as an example, the nonmonetized performance metrics for percentages of impervious surface cover and for minimum level of green space and tree canopy in each watershed. A sample of threshold values is shown in Figure 9.18 (see page 186). These are performance standards that can be applied in conjunction with the monetized performance standards discussed in the previous section. Included with the nonmonetized measures is the use of tools for internalizing the costs of ecological services. In the figure, there is a performance metric of maximum percent impervious surface. This is coupled with the monetized

Photo credit: Barrett Walker

FIGURE 9.13

Impact of threshold conditions.

performance metric (in the form of a fee) to establish how the consumption of the ecological services will be internalized to those that "take" the service.

Figures 9.19 through 9.22 illustrate a representative application of the percent impervious surface performance metric. Historical population growth rate and land use changes in the Atlanta metro area over the past 30 years have been used to project future changes in percent impervious surface, using the geographic information system tools discussed in Chapter 13 (Figures 9.19 and 9.20; see pages 187–188). Figures 9.21 and 9.22 project the performance of the metropolitan area against the objective of controlling impervious areas under the land use policies and regulations in place as of 2008.

The performance metric in this instance is quantitative, although the scale of importance is qualitative. The critical need is to include such performance metrics, monetized and nonmonetized, into the decision settings for land use policies and regulations. In the example given in Figures 9.21 and 9.22 (see pages 189–190), the performance metrics for the current policies are population growth and economic activity. As seen in the series of figures, though, much of the economic activity is actually mining the future stability of natural systems. The development model

Photo credit: Barrett Walker

FIGURE 9.14

Impact of threshold conditions.

is exploitative because the performance metrics do not enable decision makers to see the consequences of their failure to appropriately define and internalize environmental costs.

9.2.5 Application of Sustainability Performance Metrics

The performance metrics discussed in the following pages can help the decision maker understand the relative consequences of alternatives under consideration. However, their functionality extends well beyond that of mere analysis; they are equally useful for examining strategic and tactical ways to improve the likelihood of designing and implementing sustainable practices. Performance metrics should provide the ability to internalize costs to the beneficiaries.

This is not as simple as imposing the cost of loss of services on a particular property owner who is changing his land use. There are two dramatically different points of view. The individual who develops the land into an impervious surface is benefiting from the conversion and taking ecological services from society. Conversely, society had been taking those ecological services from the property owner without compensation.

Who owns the ecological services of a particular piece of property? This is not well conceptualized under current property law. Something easily measurable

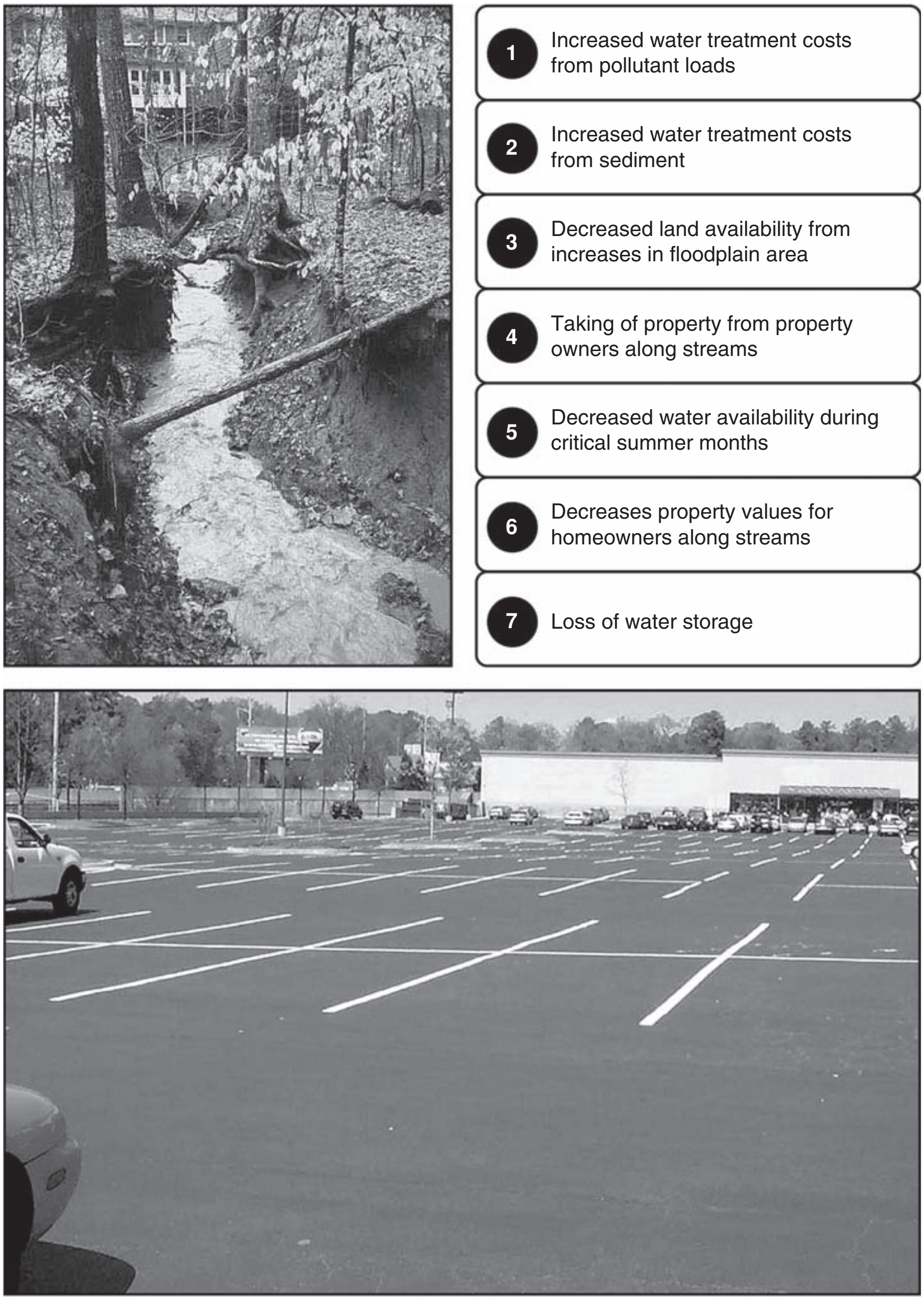


FIGURE 9.15

Characteristics of land use alterations. Photos used with permission of Upper Chattahoochee Riverkeeper.

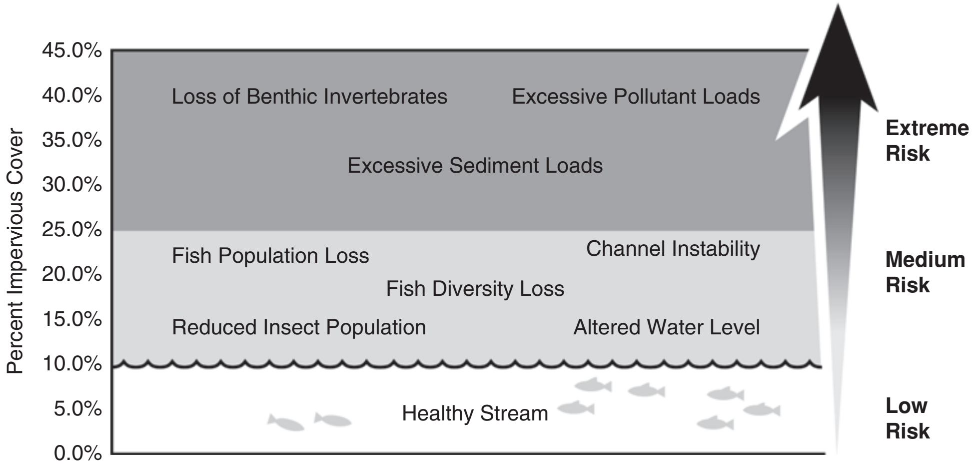


FIGURE 9.16

Impact of threshold conditions.

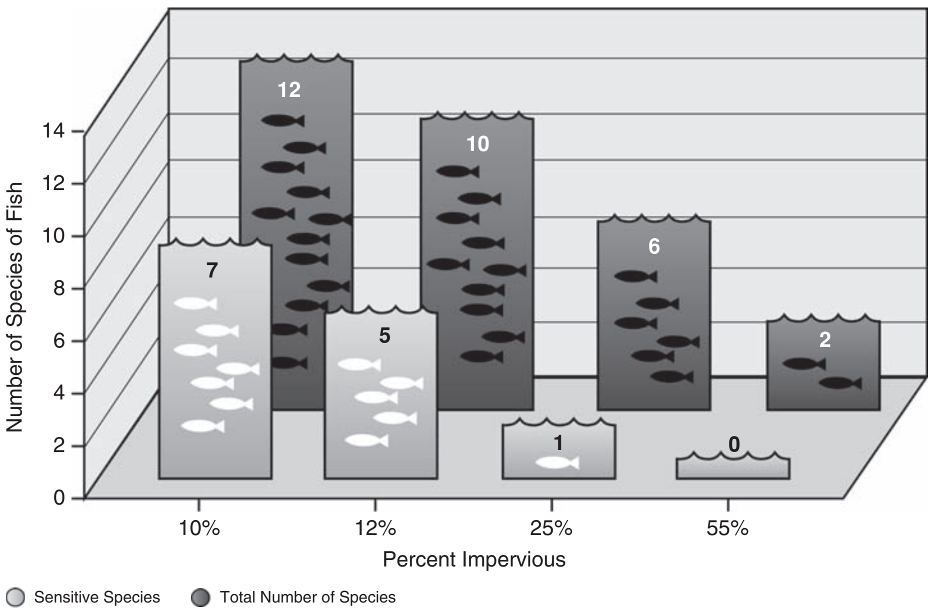


FIGURE 9.17

The impact of threshold conditions. The fish population is a measure of water quality and availability. Therefore, declining fish population is an indication of severe economic impact.

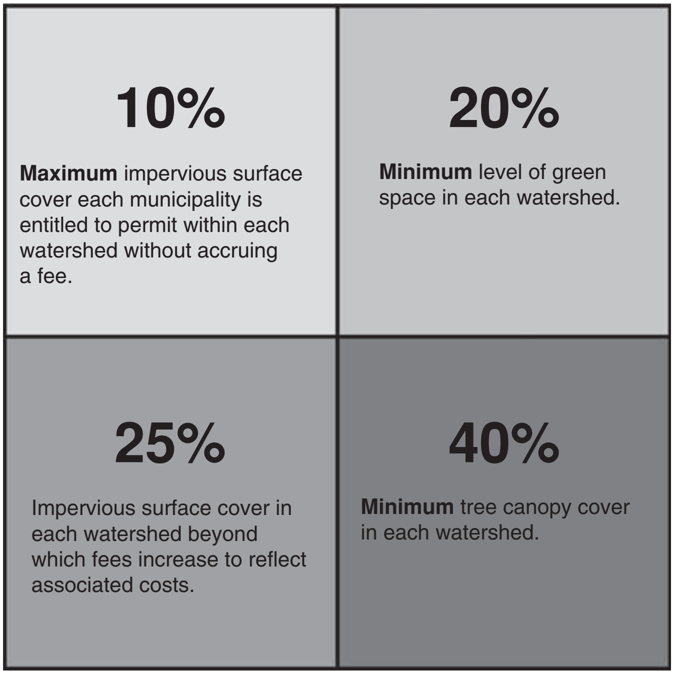


FIGURE 9.18

Proposed conceptual model.

such as sediment leaving a property can be defined as a nuisance trespass and as such controlled under the law. However, the taking of an ecological service has no similar legal precedent. Further, ecological services are generally system based and so are not easily enclosed within the discrete boundaries established by human convention to divide up the surface of the land.

From a practical standpoint, selecting strategies for using environmental performance metrics to incentivize sustainable practices is a decision setting in and of itself. One alternative is compensating rural landowners who provide ecological goods and services to society through good land stewardship. To date, the main tool to accomplish this has been to pay landowners directly to set aside portions of their land, in a shift from “polluter pays” to “beneficiary pays.”

Alternatives for internalizing the value of ecological goods and services can also be achieved through regulation, stewardship incentives under existing programs, market-based instruments, and tax rebates. In each case, assessment of the consequences of alternatives first requires an appropriate definition of the performance metrics against which the alternatives will be judged. In other words, there must be a way to measure ecological goods and services.

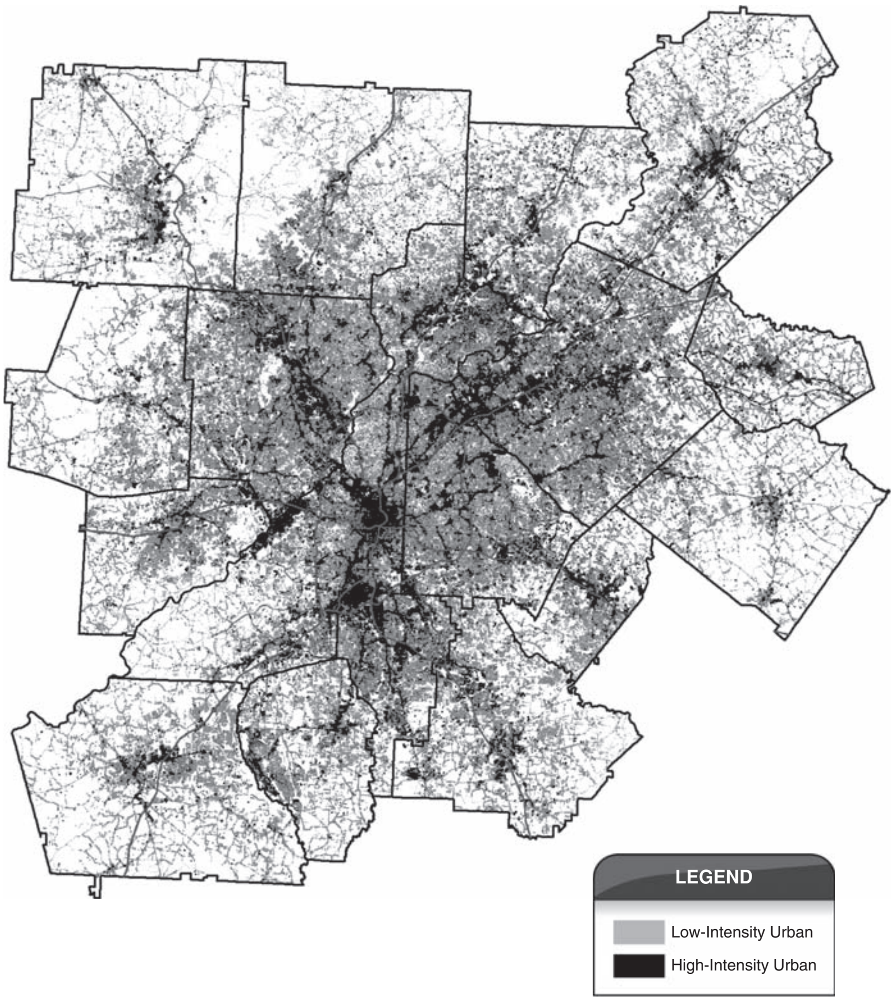


FIGURE 9.19

Metro Atlanta area impervious cover map, 2020.

9.3 NUMERICAL ALGORITHMS FOR PERFORMANCE METRICS

In a sustainability decision setting, one of the most difficult tasks is the development of performance metric algorithms for objectives that cannot be monetized in a manner that is generally accepted by stakeholders. It is very hard to generate a mutually agreeable number that captures the underlying value of a concept such as biodiversity. It is particularly difficult to define that value so that it does not

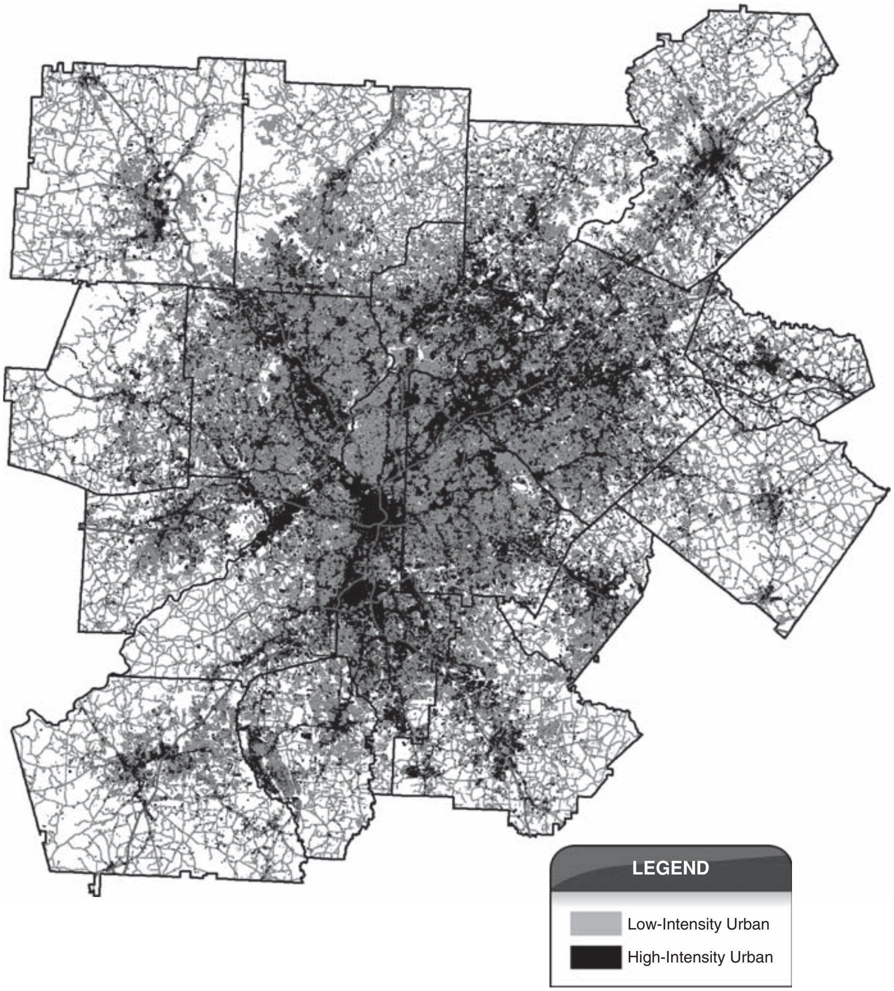


FIGURE 9.20

Metro Atlanta area impervious cover map, 2030.

merely capture advocates' beliefs on a scale of "vitally important" to "could not care less." It takes a combination of science, art, and facilitation skill to convert a qualitative value into a semi-quantifiable algorithm that, to the extent possible, incorporates experience, knowledge, and facts to clarify values.

The process described here is carried out in the following steps:

Step 1. Classify objectives to determine those that are and are not amenable to direct measurement or monetization of performance metrics.

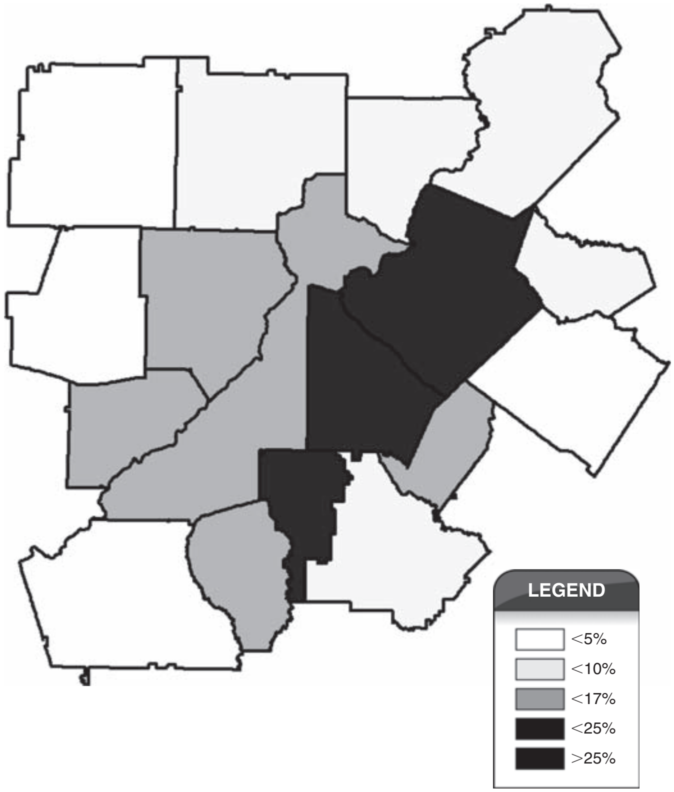


FIGURE 9.21

2020 forecasted overall regional percentage impervious average.

Step 2. Identify whether there is a measurable physical characteristic that can serve as a surrogate measure for the objective.

Step 3. Identify the domain over which the performance metric is to be defined.

Step 4. Define threshold conditions.

Step 5. Identify the performance measurement statistic—how a physical characteristic from step 2 will be measured (e.g., absolute or percent change in a physical condition such as impervious area, number of species, amount and quality of woodland, or conversion of forest to alternative uses).

Step 6. Define how the statistic will be generated—either through quantification of the physical characteristic of step 2 or through qualitative definition by the decision team. For example, the percent change in impervious area may be generated through analysis of aerial photographs from different years or estimated based on change in population density.

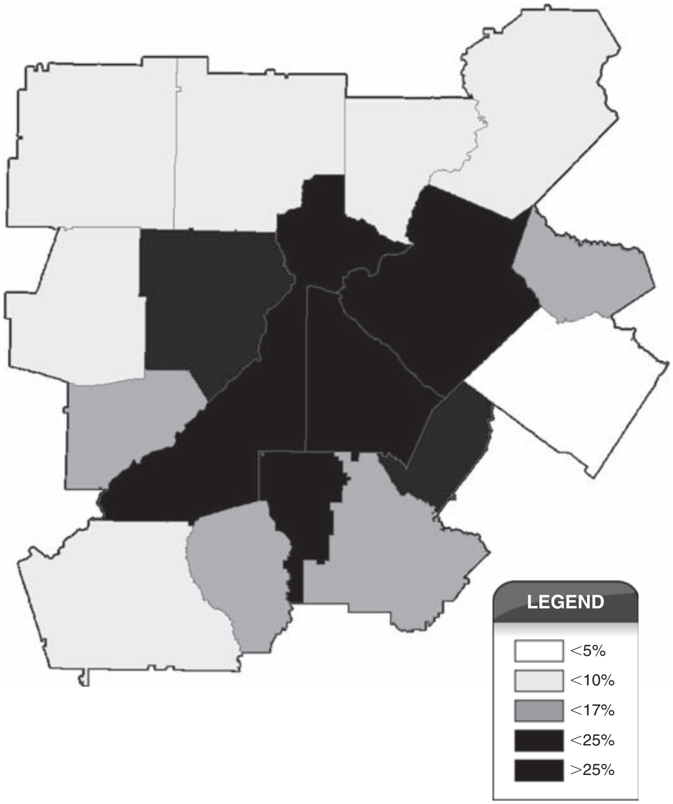


FIGURE 9.22

2030 forecasted overall regional percentage impervious average.

9.4 EXAMPLE PROBLEM: ESTUARY RESTORATION

The steps just listed will be illustrated with a hypothetical restoration of a riverine system impacted by a century of urban and industrial development.

9.4.1 Decision Setting

An estuary along the southeastern coast of the United States experienced significant industrial development within its watershed, beginning in the 1920s with the construction of a refinery for processing crude oil from the Gulf Coast. Development accelerated rapidly during World War II, with the construction of chemical plants using the refinery products as feedstock. Industrialization continued into the 1950s with the construction of chloralkali facilities and additional chemical processing plants, including various pesticide production facilities. Coupled with this industrialization was the growth of commercial and residential development in the upper reaches of the watershed.

Waste management practices in the early years of development in the watershed were limited to nonexistent. This began to change in the 1930s and 1940s with increasing public awareness that the environment could not absorb industrial waste without eventual consequences to downstream users. Waste management continued to improve through the 1950s and 1960s, but there was still significant discharge of various contaminants into the watershed's aquatic systems.

Dramatic improvement in both product and waste stream management began in earnest in the 1970s and 1980s in the United States with the passage of such laws as the National Environmental Policy Act (NEPA), the Clean Water Act (CWA), the Resource Conservation and Recovery Act (RCRA), and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Thus, by the late 1980s, new contaminant releases from the industrial component of the watershed into the riverine system were rare. In addition, nonpoint source pollution from the industrial component was largely controlled because of the effectiveness of various regulatory bodies in dealing with issues of economy of scale. Nevertheless, nonpoint source pollution from expanding commercial and residential development has increased and will continue to increase into the foreseeable future.

Contaminants of concern (COCs) include volatile and semi-volatile compounds as well as various metals, particularly mercury and arsenic. Because of the steady accumulation of sediment in the estuary, the contamination characteristics change with depth. The deeper sediments contain contaminants released in the past; the shallower sediments represent more recent releases. The sedimentation rate in this estuary was relatively consistent up through the early 2000s because of widespread regional land subsidence associated with groundwater pumping. As the land subsided, the depth of the riverine system stayed in equilibrium though a buildup of the sediment pool.

Regulatory agencies and the estuary's industrial facilities began to collaborate to restore the riverine system in the 1990s. The overall goal was to ensure that it had an acceptable level of ecological health and that it was not a contributor to the degradation of the larger ecosystem, which included extensive, ecologically productive downstream saltwater estuaries. Data collection was conducted over a 15-year period. However, overlapping regulatory programs and the large number of parties—both past and present—sharing responsibility for impacting the system made it difficult to achieve a resolution.

The lack of resolution has been exacerbated by the fundamental problem of defining a practical and meaningful performance metric. Regulatory programs fall back on measures of ecological or human health risk or concepts such as maximum total daily load and simple threshold criteria. The weakness of these concepts is that they are one-dimensional and derived through a long chain of poorly understood assumptions. In addition, they are frequently either impractical to implement or their implementation can create ancillary impacts equal to or greater than what is being resolved.

9.4.2 Deriving Performance Metrics for the Restoration Project

A conceptual representation of the problem setting is provided in Figure 9.23. The following sections outline the process of deriving a performance metric that allows the assessment of alternatives against nonmonetized objectives.

Step 1: Classify the Objective: Identify the Objectives That Are or Are Not Amenable to Direct Measurement or Monetization

Our restoration project for the riverine system has three objectives. Two are amenable to relatively straightforward performance measurement; one is not.

Objective 1. Minimize the long-term human intervention needed to maintain the health of the ecosystem.

Objective 2. Ensure a positive and acceptable rate of human health and ecological risk reduction to a risk-based endpoint.

Objective 3. Maximize the net ecological system benefit per unit of invested resources.

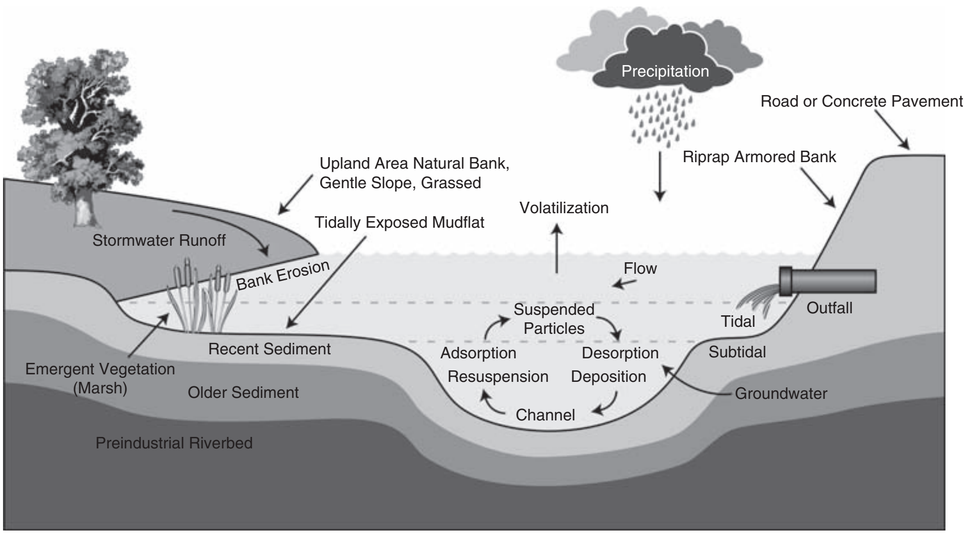


FIGURE 9.23

A conceptual representation of the problem setting.

Objective 1 Classification (step 1): Threshold sustainability objectives and performance metrics

The first objective—minimizing the long-term human intervention needed to maintain the health of the ecosystem—is presented as a threshold condition in any decision setting in which sustainability is to be incorporated into the decision context. The need for continuing human intervention implies that the system will retain some level of imbalance. Any long-term human intervention requirement means that the alternative selected can eventually be subject to a new failure. Human intervention requires that energy and resources be diverted from other needs to continuously maintain the selected alternative. However, there is no guarantee that the energy and resources will continue to be available or that events beyond anyone's control will not divert them to satisfy more pressing needs.

The performance metric for this objective is relatively straightforward both to measure and to predict. It is also relatively straightforward to monetize. Note that the monetization can take several forms. One is conversion into present-day dollars. Other currencies based on physical realities can be used. The most obvious are energy and greenhouse gas emissions. Both have the advantage of being a measure of tangible values or costs.

Moreover, energy or carbon emission monetization units have an advantage in the robust information they provide regarding the long-term consequences of different alternatives. Dollar monetization invariably discounts future costs. For sustainability, though, this should not be the case. In fact, future costs should have a reverse discount. A unit of energy or a unit of greenhouse gas emissions 30 years from the present is almost certain to be much more costly than the equivalent unit today. Physical monetization units don't decrease in value over time, and in fact may become a limiting threshold consideration in assessing the impact of alternatives.

Two alternatives that have an identical present-day dollar value for long-term maintenance may appear radically different in terms of the distribution of greenhouse gas emissions or energy requirements. An alternative that has high up-front costs but long-running benefits in energy reduction (through climate moderation, for example) or carbon sequestration may look much better than an alternative that has a low discounted present value.

Objective 2—Classification (step 1): Achieving a positive rate of change

The second objective—ensuring a positive and acceptable rate of human health and ecological risk reduction to a risk-based endpoint—captures the fact that it is seldom possible or even desirable to achieve an ideal final condition for an ecosystem, especially as the target system grows in scale and complexity. A more functional objective is to positively influence the ecosystem's natural functions in a manner that permits it to repair and maintain itself. The objective should be to eliminate, reduce, or manage the stressors so that the ecosystem can evolve back into a dynamic equilibrium that resembles, as closely as possible, a self-sustaining natural system.

Objective 2 can use as a performance metric the rate at which environmental stressors are changing. In the situation described for the estuary, this can include a variety of variables that can be measured and predicted, including the rate of change in contaminant concentrations in the food chain and the rate of change in the number and variety of species across different trophic levels. An assessment conducted over time yields estimates of the baseline conditions of these metrics and allows probabilistic predictions to be made regarding the reaction of the metrics to various alternative programs for restoring the ecosystem.

In addition to being monetized, the metrics of physical characteristics can be used in and of themselves. For objective 2, then, there can be multiple metrics that give the decision team a means to assess the relative impact of alternatives. There is an advantage to having both physical and monetized performance measurements. The weakness of an objective such as this one, with no other consideration, is that there is no absolute standard. What is an acceptable rate of improvement, what is the time period of acceptability, and what is the endpoint? No absolute rate of change or difference in rate of change exists between one alternative and another that is itself a threshold standard.

The third objective provides an additional means to objectively assess the relative value of the first two objectives.

Objective 3 Classification (step 1): Maximize net ecological system benefit per unit of invested resources

The first two objectives can be measured, even though they too are subject to extensive assumptions and uncertainty. Their primary weakness is the absence of an absolute standard.

The third objective introduces utility into the assessment through the concept of net ecological system benefit, which has its own vagueness. Net ecological system benefit has no ready scale on which to judge alternatives. What is meant by quality, natural diversity, or even ecosystem production? However, by introducing utility, or the return on some measurement scale, it is possible to at least compare the *relative impact* of invested resources.

A relative comparison provides an additional tool with which decision makers can assess practicality. The oft-used stipulation for environmental remediation is *as practical*, but this term is problematic: Who defines what is practical? The extent to which an effort is practical is hugely dependent on who is paying for it or who is ultimately responsible for implementing it. An effort that may look practical to a group sitting comfortably in an air-conditioned office can appear radically different to the individual or company in the field actually expending the energy and resources.

Summary of Step 1

Objectives 1 and 2 have relatively straightforward performance metrics. The first objective—minimize long-term human intervention needed to maintain the health of the system—can be measured by the number of man hours and the amount of energy and resources required each year to maintain each alternative. The second objective—ensure a positive and acceptable rate of human health and ecological risk reduction—can be measured by the rate of change in measurable physical characteristics such as contaminant concentrations and number and diversity of species.

The third objective—maximizing the net ecological system benefit per unit of invested resources—has two parts. The first part is the capital required to implement each alternative. This is relatively straightforward and can at least be estimated within an objective framework that is easy to document, reproduce, and explain. The second part is more difficult. Measuring ecological system benefit requires integrating a variety of physical parameters, sociopolitical issues, and values into a measure that can be easily assessed by diverse and potentially oppositional decision makers. For this, a surrogate metric is needed.

The third objective is therefore carried forward into step 2 of the performance metric development process.

Step 2: Identify Whether There Is a Measurable Physical Characteristic or Group of Characteristics That Can Serve as a Surrogate Measure for the Objective

A potential candidate for a measurable physical characteristic might be biodiversity or surrogates such as threshold levels of contaminants. However, let's assume in this setting that these measures are insufficient. The principal problem is that the ecosystem under consideration cannot be separated from the structural changes to the larger systems. It is not a matter of practicality for our decision makers in terms of potential cost. Rather, in the setting they are in, they simple do not have the means or power to effect any meaningful changes regarding the broader infrastructure problems throughout the watershed. Some conditions are beyond their control, including changes in the saline cycle due to land subsidence and urban stormwater flow, conversion of riparian buffers due to development, and nearly complete transformation of upland land cover characteristics.

Threshold physical measurements are not capable of dealing with the idea that the effort is to be focused on achieving the possible and not on striving for a perfect state that would be impossible to obtain under any condition.

The inputs to consider for developing the performance metric for objective 3 are summarized in Figure 9.24 and discussed in the following three steps. These steps identify the three primary inputs that should be considered: measurement domain, measurement threshold, and measurement statistic.

Step 3: Identify the Domain over Which the Performance Metric Is to Be Defined

The next step for developing a performance metric for objective 3 is to develop the scale over which the decision team is going to consider valuing the metric. Scale in this sense means the boundaries that define the extent of the performance. In the

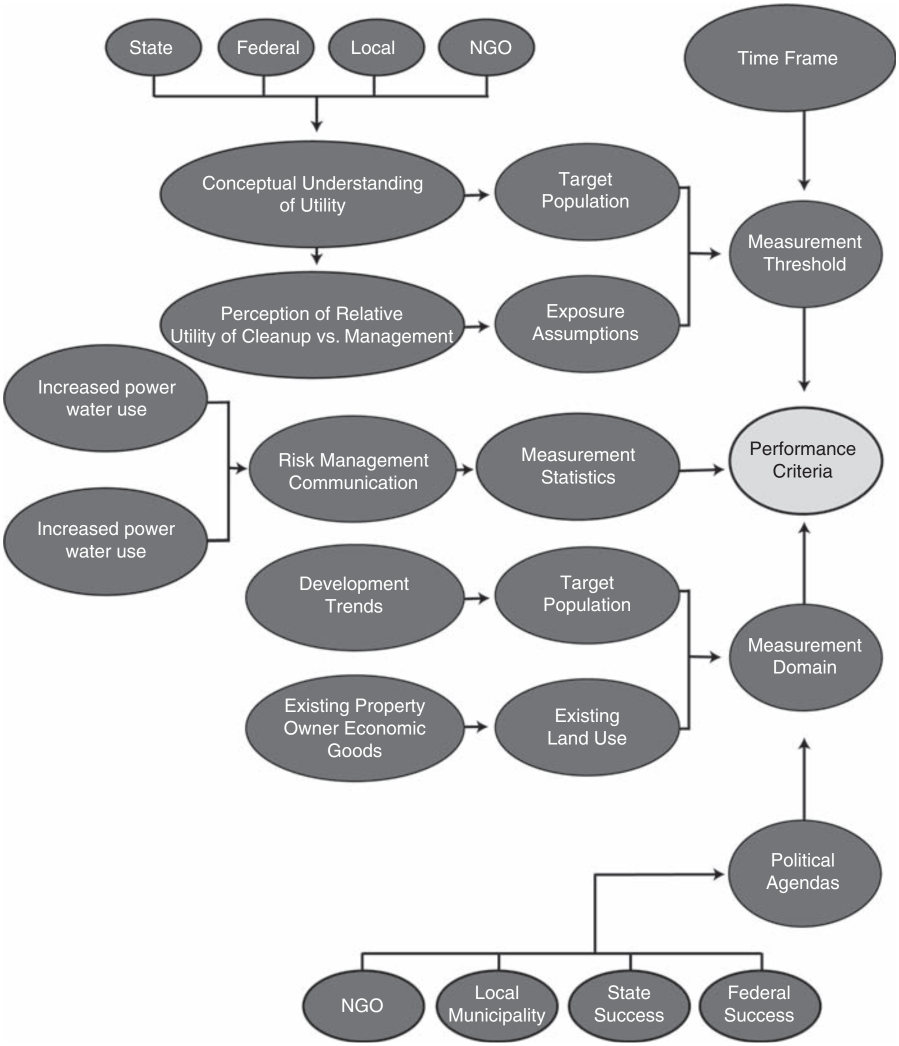


FIGURE 9.24

Summary of the inputs to consider for developing the performance metric for objective.

riverine restoration setting, the boundaries could be a segment of the estuary, an entire stream segment, the stream and its riparian buffer, or the stream's impact on the downstream system. As the decision team establishes values for the estuary, it is necessary to consider what values are being assessed: those of the estuary itself or those of its contribution to larger systems. The size and limits of the system under consideration need to be commonly understood and accepted by the decision team. Without this understanding, establishing relative values can easily become a source of conflict among stakeholders.

As shown in Figure 9.24, the domain for any problem associated with sustainability should be established with consideration for both the public and the private sectors. The public sector is driven by political agendas. These agendas will arise out of regulatory requirements, local economic considerations, and the advocacy of nongovernmental entities (NGOs). In our example, the focus on the riverine system was prompted not by the specific estuary but by its potential impact on downstream estuaries that are productive fisheries. What, then, is the domain to be assessed in terms of performance of potential alternatives? Will it be the restoration of the estuary in the industrial and urban area, the restoration of the downstream estuaries, or merely the stabilization of an existing industrial area to eliminate contaminant fluxes into the broader environment?

Clarifying the domain over which performance is to be considered should not be seen as either routine or easy. It is not uncommon, as described in this example problem, for a particular project, task, or mitigation effort to be at least partially disconnected from its larger setting. Watershed restoration, along the lines of our example, can range from restoring an entire watershed to restoring a single stream segment. In both cases, the ultimate objective is overall system restoration. Inevitably, however, the scale of problem solving is constrained by regulatory, economic, and jurisdictional boundaries.

Domain cannot be considered without private sector input. As shown in Figure 9.24, land use requirements and opportunities—existing and future—should be inputs to the determination of the domain of performance measurement (e.g., how the area can be utilized to create economic value for the existing and future communities). Ignoring the private sector in setting the appropriate goal can be counterproductive, as it will frequently be the primary or critical source of funding.

In this example of the estuary, the domain selected for measuring improvement is the specific estuary and not the areas downstream.

Step 4: Identify the Threshold Condition

Defining the threshold condition or conditions refers to setting the conceptual boundaries of performance. For example, the objective we are trying to measure is maximization of net ecological system benefit per unit of invested resources.

In the previous step, the decision team decided to focus on the specific estuary in assessing the performance of alternatives in achieving this objective. What needs to be addressed now is the threshold condition to use as the baseline. In other words: On any qualitative scale, what is the condition that we are comparing against? Is it the status of the estuary now, or is it the status of the estuary in 10, 20, or 30 years if existing trends continue?

We can be sure that the estuary will experience some changes in condition due to outside interventions that have already taken place. For example, at least some of the stressor inputs, particularly the ongoing discharge of contaminants from the industrial facilities, will continue to diminish; also, ongoing sediment rates will, over time, lessen the relative impact of past contamination and increase the relative impact of ongoing urban runoff contamination. Estimating the performance of alternatives requires that the decision team have a common understanding of what condition is serving as the basis for the comparison. Is it the current condition, the condition that the estuary will evolve to at some point in the future, or the rate of change itself?

Figure 9.24 illustrates that other considerations come into play in establishing the measurement threshold (or baseline) for estimating benefit versus unit of invested resources. The decision team must reach agreement about what constitutes the target populations and about exposure assumptions. Mutual understanding of each decision team member's idea of utility is also needed.

In our example, the issue of measurement threshold comes into play with respect to the fact that the estuary is in the middle of both a highly industrial area in its lower reaches and a rapidly developing urban and residential area in its upper reaches. Does it make sense to try to restore the estuary in such a way that it becomes an attractive habitat for a variety of higher-trophic-level animals and birds such as otters, beavers, and piscivorous birds, especially in the middle of an industrial area? Should the measurement threshold instead concentrate on the stressors to the sediment and the lower trophic levels?

For our example, let us assume that the decision team elects to use a target threshold condition for the sediment quality and the lower trophic levels, and not to attempt restoration of the estuary for the upper trophic levels.

Step 5: Identify the Performance Measurement Statistic

The measurement domains and measurement threshold considerations of steps 3 and 4 are necessary so that each decision team member can consider the measurement statistic with the same underlying conceptual model of the scope and boundaries under consideration.

In our example, the measurement is going to focus on the specific estuary and on the characteristics of the sediments within it. Selecting the performance measurement statistic requires the decision team to identify what characteristics of the estuary sediments can be collectively assessed and whether they can be assessed qualitatively, quantitatively, or in combination. However, it should match the characteristics of a performance metric:

- It provides a measure that a decision team agrees is a functional surrogate for its collective understanding of the objective.
- It provides a clear and unbiased comparison of alternatives.
- It is amenable to disaggregation of underlying components to simplify the assessment of uncertainty.
- It is composed of scalable characteristics, even if they can only be scaled qualitatively.
- It provides a measure of threshold requirements.

An example for our estuary is shown schematically in Figure 9.25 as the current condition of the estuary. The first part of the performance statistic is the sediment stressors. The objective is to **maximize net ecological system benefit per unit of invested resources**. The previous steps focused on the targeted ecological system benefit of stabilizing the sediments biologically. A surrogate for this would be managing the stressors affecting the biological stability of the sediments. The change in the stressors, whether they can be measured or are derived through collective judgment, is a number that allows the alternatives to be compared directly, satisfying the second performance characteristic just listed.

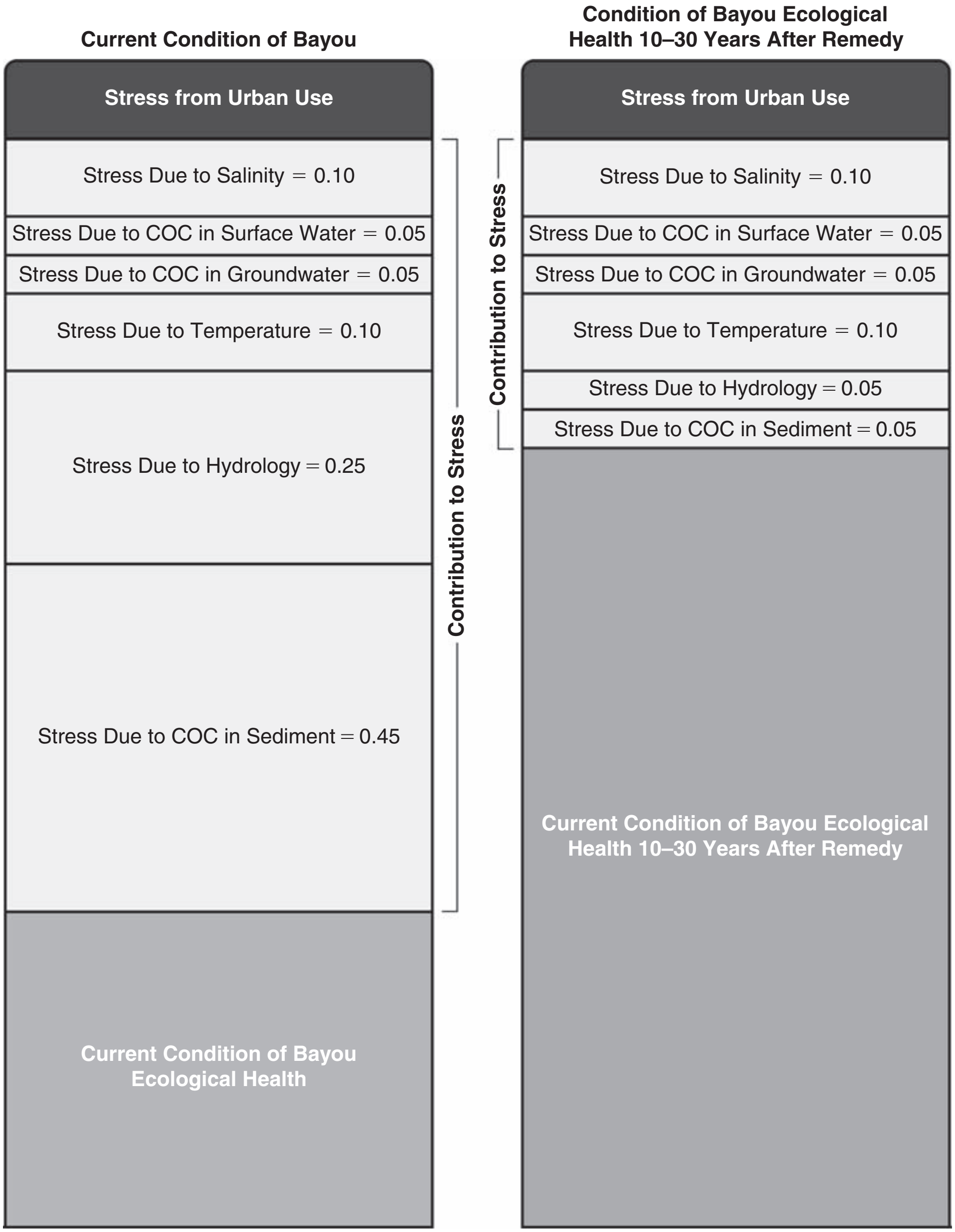
As shown in Figure 9.25, the stress on the estuary can be disaggregated to allow the decision team to consider the effects of alternatives on its individual components. The resulting disaggregated stresses arise from the salinity regime, ongoing contaminant contributions to the sediments (from surface water or groundwater), cyclical temperature changes, hydrologic changes, and the existing COC inventory in the sediments.

Each stressor can be scaled relative to the others and relative to its likely changes under various alternatives. Consider a situation in which the relative stress due to hydrologic regime modifications is many times worse than the stress to the active biological zone from contaminants in the sediments. This can occur where the majority of the COC inventory is below the biologically active zone and the buffering of wet and dry season flow volumes and flow rates have been eliminated by pavement in the basin. In this situation, the biological activity in the near surface sediments may be impacted almost completely by the stress of the severe changes in hydrology with little to no effect from buried past contamination.

Finally, the performance statistic provides a means to establish threshold requirements. As shown schematically in Figure 9.25 as the condition of the estuary 10 to 30 years after the remedy, many of the stressors cannot be altered by anything within the power of the decision-making group. Complete elimination of the COCs in the sediment may increase the estuary's ecological health, but salinity, ongoing surface water runoff from urban areas, groundwater discharges, temperature, and an altered hydrologic regime will maintain a baseline level of impact in the estuary.

This is an important consideration in developing an estimate of the actual utility of any particular alternative in relation to its cost. Imagine in Figure 9.25 that the scale of the bar graph is 0 to 10 from bottom to top. On this qualitative scale, the current condition of the estuary sediments is collectively selected by the decision team to be approximately 3.5. After extensive removal of contaminated sediments, the health of the estuary 10 to 30 years later may have improved only to about 5.5 on a scale of 0 to 10—with 10 being pre-Columbian conditions and 0 being an elimination of the estuary with a covered culvert.

The second part of the performance statistic is the cost per number of qualitative units of improvement. Assume that two alternatives are examined. Alternative 1, costing \$40 million, involves removing all sediments. Alternative 2, costing \$5 million, involves leaving the buried sediments in place and constructing



% Reduction in Degradation Units = Current Condition × Percent Elimination [0.45 × (0.45 − 0.05)]

0 = No ecological benefit 10 = Pristine ecological benefit

FIGURE 9.25

Threshold conditions.

sediment control structures to prevent surface erosion that would allow buried sediments to reach the bioactive zone.

Alternative 1 improves the relative, qualitative measure of sediment ecological health from 3.5 to 5.5 at a cost of $20 million per unit of improvement. In contrast, alternative 2 improves the sediment ecological health from 3.5 to 4.0 at a cost of $10 million per unit of improvement. The decision team can also consider whether there is a material advantage, or a threshold benefit, in improving to 5.5 versus 4.0. This becomes a question of determining collectively whether confidence in the expectation of improvement between the two alternatives is sufficient to justify the higher investment in resources and money.

Step 6: Define How the Statistic Will Be Generated—By Quantification of Step 2's Physical Characteristics or Decision Team's Qualitative Definition

For a qualitative statistic such as that discussed in the previous step, it is necessary to employ a procedure that captures the experience, knowledge, and perspectives of the decision-making team. The tools of Facilitated Decision Consequence Analysis, as discussed in Chapter 21, are helpful here. A simple framework is the polling approach, followed by team analysis and adjustment as the participants explain and debate their particular choices. A potential response from a participant regarding the relative impact of stressors is provided in Figure 9.26.

In the polling approach, each participant is asked to apply a value of 0 to 1 to each stressor. This value should reflect individual perceptions of the percent that each stressor contributes to the *total* stress on the estuary's ecological health. A value of 0 means no contribution; a value of 1 means that all of the stress is associated with that particular stressor. The sum of all stressor values assigned by a participant must equal 1.

The second piece of information obtained from the participants is their perception of the estuary's current condition. A pristine estuary is 10; a concrete pipe is 0.

Stressors	% Contribution to Degradation of Ecological Health Participant 1 Values
Tidal Influence	20%
Storm Surges	20%
Contaminants in Groundwater	5%
Contaminants in Sediments	35%
Contaminants in Surface Water	5%

FIGURE 9.26

Qualitative assessment of stress contribution.

These numbers are used as a basis to rate the current condition. The state of knowledge and belief about the estuary can then be collected from participants, based on the value they choose.

Finally, information can be extracted regarding knowledge and beliefs about the likely reduction in stress to the estuary under several alternatives, as shown in Figure 9.27. Each alternative can have varying effects on reducing the stress on the estuary's ecologic health caused by each primary stressor. For instance, removal of the impacted sediment mass will eliminate most, but probably not all, of the stress associated with it. The inability to eliminate 100 percent of the stress is due to the impossibility of removing 100 percent of the sediment and to the fact that resuspension of very high historical contamination currently deeply buried can occur. Therefore, the estimated range of reduction from this stressor is more likely 75 to 90 percent.

A removal alternative, though, may have zero effect on any stress caused by groundwater COC flux into the estuary. In this example, the decision team can assess uncertainty and the range of perceptions by obtaining the minimum, maximum, and most likely percentages by which each participant thinks each alternative may reduce the stress contributed by the primary condition. Figure 9.27 presents an example qualitative assessment of ecological health under the baseline condition (natural recovery) and several alternatives.

The final component of the performance metric generates the utility. A cost for each alternative can be estimated. The cost and improvement metrics can be combined into the performance metric as shown in Figure 9.28. This metric combines qualitative and quantitative assessments of the objective to improve the environment with a practical and reasonable allocation of resources.

In the example shown, none of the alternatives can realistically return the estuary to anything near pristine conditions, as the stressors are simply too many, too independent, and too complex. Removal of all contaminated sediment may seem, intuitively, to be the correct direction at the outset. However, the performance

Sediment Remedy	Average Minimum	Average Maximum
Natural Recovery	0.28	0.56
Impervious Cap over Sediment	0.40	0.60
In situ Treatment	0.43	0.71
In situ Bioremediation	0.29	0.54
Sediment Removal	0.75	0.90

FIGURE 9.27

Results of polling of reduction in stress to estuary.

Path	Alternative Description	Relative Resource	Units of Improvement	Utility (Millions/Unit (Stress Eliminated)
3	Sediment—Natural Recovery	8	**0.60**	**13**
8	Sediment Limited Removal—NR—Hydrology—Stabilization of Flux	27	**1.51**	**18**
9	Sediment Limited Removal—CAP—Hydrology—Stabilization of Flux	41	**1.70**	**24**
4	Sediment—CAP	22	0.70	32
1	Sediment—In situ	31	0.69	46
6	Sediment—In situ—Hydrology	50	1.07	47
5	Hydrology—Retention + Weir	18	0.36	52
7	Sediment—Removal Treatment Hydrology	72	1.23	59
2	Sediment—Removal Treatment	53	0.74	73

FIGURE 9.28

Net ecological system benefit per unit of invested resources.

metric forces the decision team to consider whether that is a reasonable expenditure of resources. This consideration becomes particularly important when it is possible, through an appropriately defined performance metric, to identify nearly equal but much less costly alternatives. Additional details on model simulation are provided in Chapter 10.

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CHAPTER

Model Simulations

10

William L. Hall

10.1 INTRODUCTION

Previous chapters discussed approaches for understanding a decision setting, construction of a decision context, graphical representation tools, and approaches for analyzing performance. This chapter addresses modeling complex decision settings in which multiple uncertainties affect the performance metrics and decision trees and influence diagrams are insufficient.

As uncertainties accumulate in real-world problems, the impact on performance metrics quickly becomes an analytical nightmare. For example, a symmetrical decision tree with just five uncertainties in sequence, with each having three discrete outcomes, has 243 branches. Doubling the number of uncertainties increases the number of branches to 59,049. Even a decision with only five uncertainties is unmanageable using a graphical decision tree. Yet decision analysis is greatly enhanced by the increasing disaggregation of uncertainties, which allows the analyst to consider each one with as few moving parts as possible. The two needs are contradictory: the desire to disaggregate uncertainties and the need for analytical practicality.

One method for dealing with large amounts of data is Monte Carlo simulation, which, coupled with the power of electronic spreadsheets and simulation software, is a powerful tool for creating the analytically rigorous performance metrics needed for conducting the type of decision consequence assessments described in Chapter 11. This chapter describes the Monte Carlo technique and the commercial software available, and provides an example application.

10.2 MONTE CARLO ANALYSIS

Monte Carlo simulation uses random numbers and probability to solve problems. Random number inputs are generated for uncertain values, which can then be processed to evaluate many independent combinations of those inputs. The

DOI: 10.1016/B978-1-85617-797-9.00010-1

term for this analytical technique, Monte Carlo, was coined by Metropolis and Ulam (1949) in reference to games of chance popular in the casinos of Monte Carlo. The process simulates the outcomes of multiple gambles over and over, relying on a large number of trials (or simulations) to define the outcomes' probability distribution.

Theoretically, the probability distribution of the outcome could be determined by mathematically combining all of the input distributions. In reality, though, such an approach is complex and beyond the grasp of nonmathematicians. The advent of modern spreadsheet software, however, allows any analyst to build the simulation models necessary for deriving outcome distributions.

A Monte Carlo analysis incorporates random variation, uncertainty in the state of knowledge, and the range of potential errors in assumptions. It produces estimates of performance, performance range, and the reliability of one or a group of alternatives. Inputs are randomly generated from probability distributions of an actual population of subject variables. The population of values for a given input is unlikely to be precisely known, but, recalling the discussion in Chapter 8 regarding the Bayesian approach, we are able to use prior knowledge to choose input distributions that we think are most likely. The data generated from the simulation can be represented as probability distributions (or histograms) and can be converted to error bars, reliability predications, tolerance zones, and confidence intervals.

The steps in a Monte Carlo simulation, which correspond to the uncertainty propagation shown in Figure 10.1, are best summarized by Wittwer (2004):

1. Create a parametric model: $y = f(x_1, x_2, \ldots, x_q)$.
2. Generate a set of random inputs: $x_{i1}, x_{i2}, \ldots, x_{iq}$.
3. Simulate the model and store the results as y_i.
4. Repeat steps 2 and 3 for $i = 1$ to n.
5. Analyze the results using histograms, summary statistics, confidence intervals, and so forth.

Step 1 is the algorithm that is used to generate a particular performance metric. Its form is dictated by the objectives of the decision setting and the definition of each performance metric. A simple example is economic performance, or any environmental or social objective that can be monetized. The parametric model or algorithm can be as simple as the addition of the various monetized costs and benefits for the disaggregated uncertainties.

The algorithm can become more complex—or more difficult to construct with consensus—for performance metrics that are qualitative or not easily translated into a common, recognized unit of exchange. These qualitative metrics include environmental or social indicators subject to personal values, opinion, and advocacy. However, the components of such an environmental or social indicator can be disaggregated, and qualitative scales can be developed that serve as surrogate measures of relative value or cost.

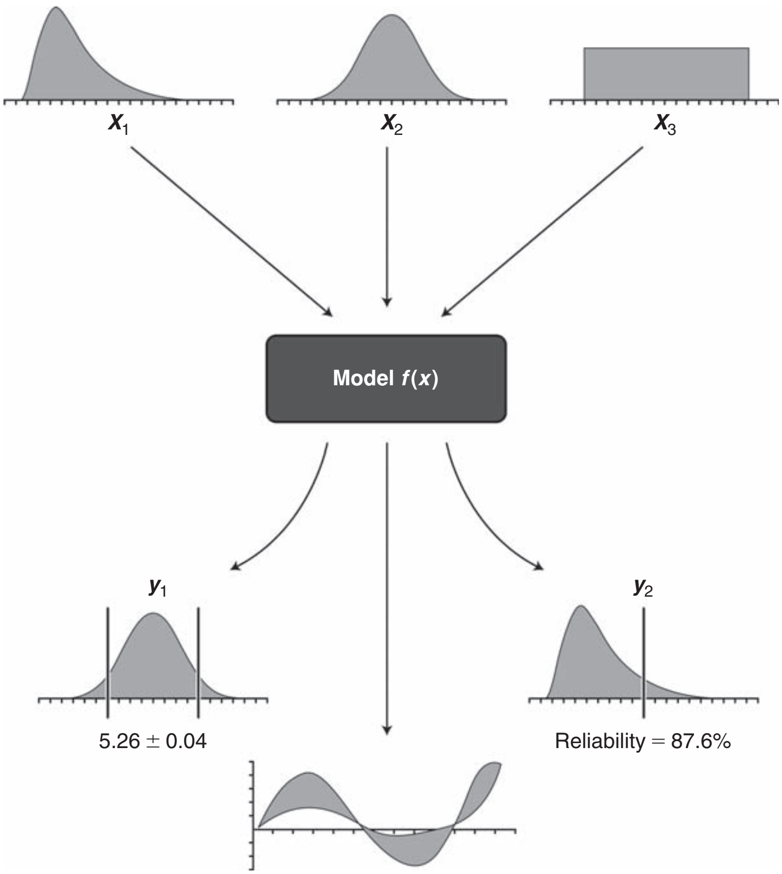

FIGURE 10.1

Schematic showing uncertainty propagation. *Source*: Adapted from Wittwer (2004).

As an example, steps 2 through 4 will be used to select a value for the variable inputs and generate a simulated estimate of y using a random number x. The process consists of the following tasks:

Task 1. Using the parametric model from step 1, identify every input variable that has an uncertainty range (i.e., those that need to be assessed as a probability distribution rather than as a fixed value).

Task 2. For each uncertainty, determine the distribution of the variable. In Figure 10.2, the variable is the number of days required to complete a certain activity. The curve represents the probability that has been assigned: five days is given

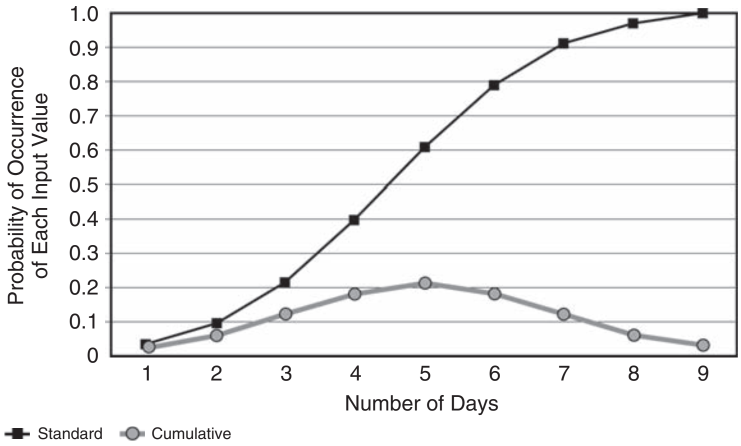

FIGURE 10.2

Converting a distribution to a cumulative probability curve.

the highest probability of around 21 percent, six and four days are given the next highest probability of around 18 percent each, and so on, to form a normal distribution curve peaking at five days (typical distribution curves are described in Section 10.3).

Task 3. Convert the distribution into a cumulative distribution curve (this step can be performed using various available software packages discussed in Section 10.4). The cumulative curve in Figure 10.2 shows about a 60 percent chance that the number of days will be equal to or less than five, and a 90 percent chance that the number of days will be equal to or less than seven.

Task 4. Generate a random number between 0 and 1 using a random number generator. Various available software packages, including spreadsheets such as Microsoft Excel, will do this automatically.

Task 5. Select an input value from the random number as shown in Figure 10.3. Line A in the figure is the random number generated between 0 and 1. Line B is the variable selected as the input value for the algorithm for one specific simulation. Lines C and D represent the random number and variable value selected in a subsequent simulation. There are software packages that will do this automatically, given the variable's distribution curve and range.

Task 6. Perform the calculation of y based on the set of selected values for the input variables.

Task 7. Repeat tasks 4 through 6 as many times as needed to develop a robust set of estimates for y. The various available software packages can perform hundreds and even thousands of iterations in a very short time.

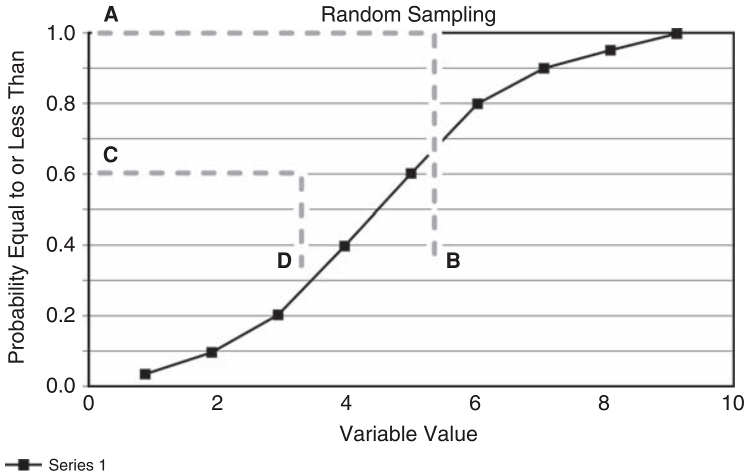

FIGURE 10.3

Generating input values.

The types of output that can be generated using Monte Carlo simulation are shown in Figures 10.4 through 10.9. One type is the cumulative consequence curve, a measure of the distribution of the predicted performance metric. The cumulative consequence graphs in Figure 10.4 provide a powerful and simple overview of the consequences of alternatives. The difference between the two alternatives shown is obvious: There is a much higher probability of lower costs with one alternative than the other.

Information can be gleaned from just a cursory look at the graphs: The level of uncertainty is indicated by the slope of the curve, and the starting point (where probability = 0) indicates whether conclusions regarding the best alternative might be sensitive to realistic changes in assumptions. In the example in Figure 10.4, the lower-costing alternative also carries significantly less uncertainty, indicated by its steeper slope. In addition, there are no apparent opportunities to alter the more expensive alternative to render it competitive, indicated by the starting point of the curve (i.e., there is a 0 percent chance that the alternative will cost less than about $375 million).

The cumulative curve is also an analytical tool for targeting the highest value opportunities for managing uncertainty to improve an alternative's performance. For example, the cumulative consequence curve in Figure 10.5 has a relatively flat slope, which is an indication of high uncertainty. The mitigation curve represents the same alternative but with mitigation of the critical uncertainties.

Additional analysis tools are available for determining and quantifying the impacts of critical uncertainties. The best is the tornado diagram, shown in Figure 10.6, which provides a quick examination of the magnitude of specific

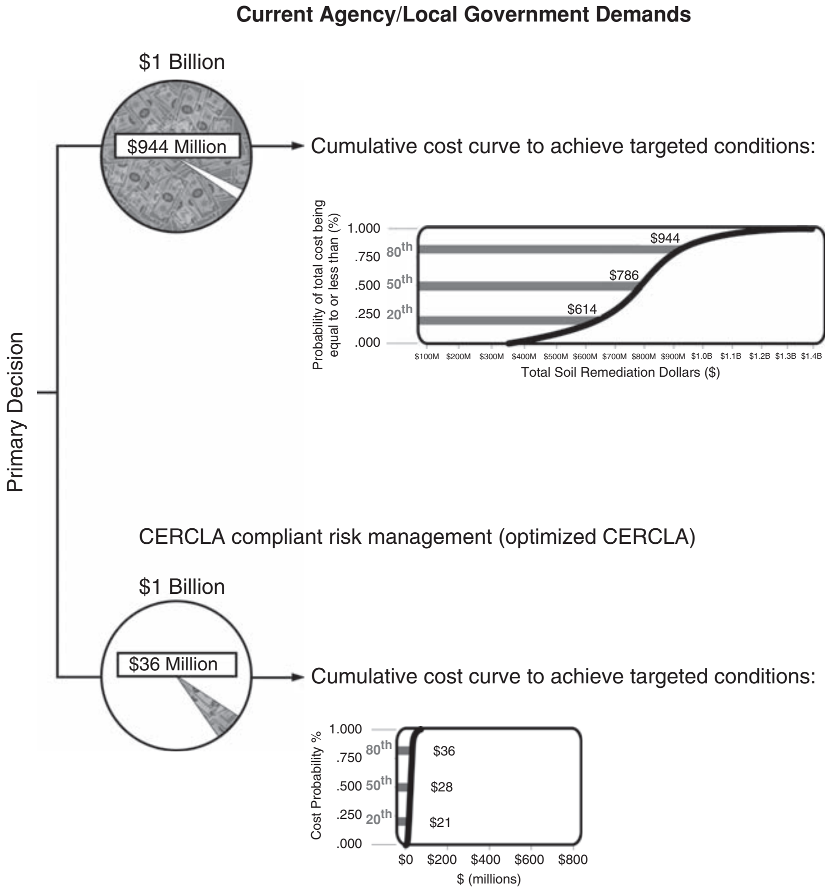

FIGURE 10.4

Cumulative consequence curve.

uncertainties' contributions to the simulated consequences on a performance metric. Another way of showing the same information is a pyramid diagram. In the example shown in Figure 10.7, assumptions regarding the background concentrations of a particular metal are the driving uncertainties associated with the restoration of an old mining site.

The trend chart is an effective way to examine the contributions of critical uncertainties to the overall performance metric. As shown in Figure 10.8, it provides the range of uncertainty associated with each input as well an efficient way to examine the range and shape of the input uncertainty.

Multi-dimensional scatter plots, as shown in Figure 10.9, are an effective tool for examining how uncertainties may be moving the predicted results in tandem

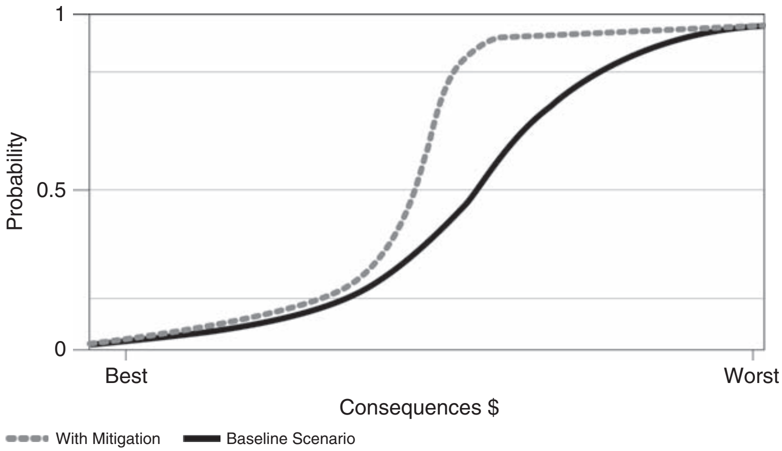

FIGURE 10.5

Interpreting cumulative consequence curves.

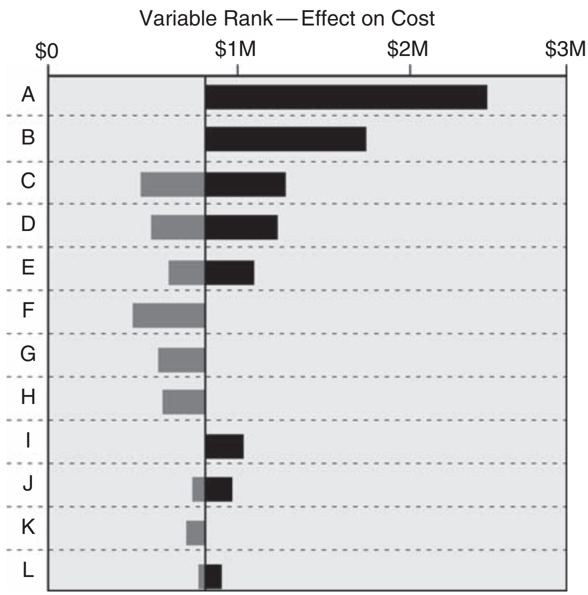

FIGURE 10.6

Tornado diagrams: effects of key decisions on costs.

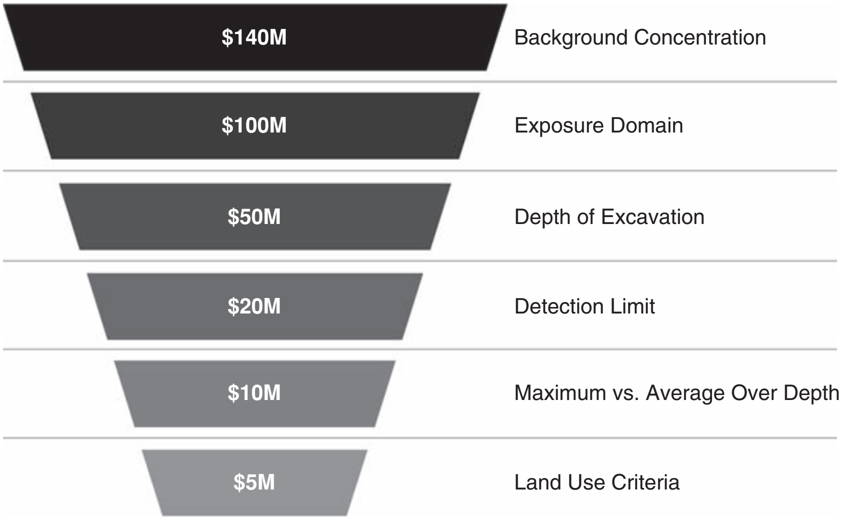

FIGURE 10.7

Pyramid diagram: most significant risk measurement criteria.

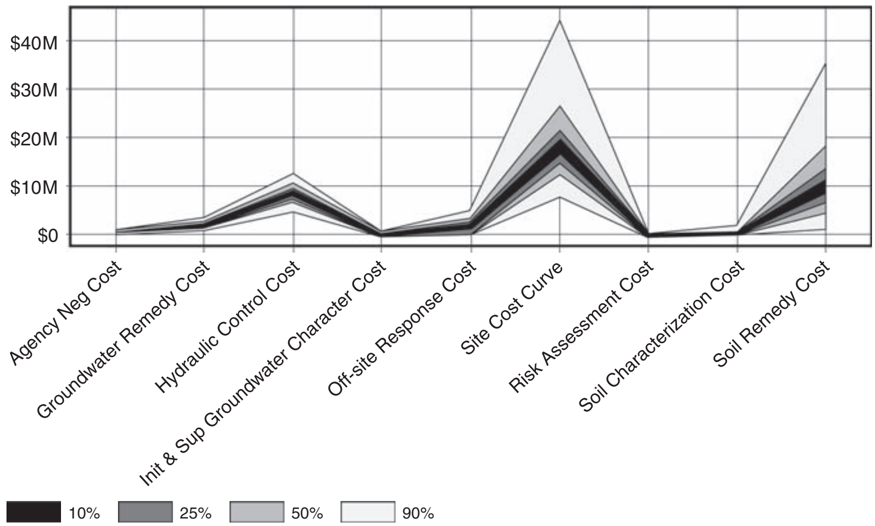

FIGURE 10.8

Trend charts.

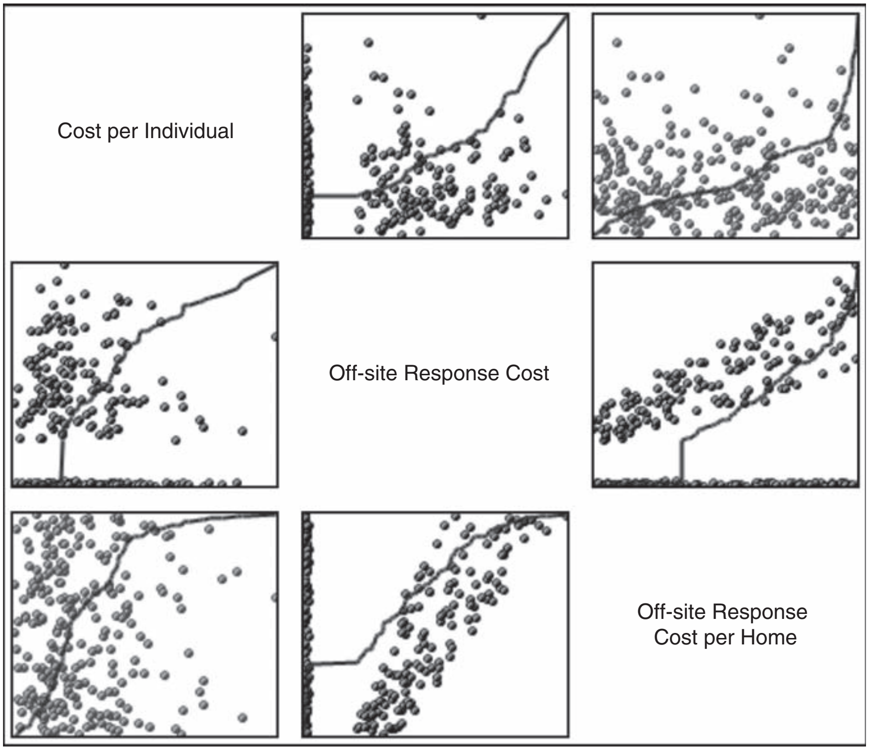

FIGURE 10.9

Multidimension scatter plots.

or opposition. The software packages discussed in the next section allow the correlation of input variables. Often, though, some correlations will not be obvious while the algorithm or parametric model is being constructed.

10.3 SIMULATION SOFTWARE

The two most commonly used and powerful commercial simulation packages are Palisade @RISK and Oracle Crystal Ball, which both operate within Microsoft Office Excel. A simpler alternative is SIM.XLA, designed primarily for teaching, which features parameterized simulation for sensitivity analysis and several random number generators. It is also possible to use the built-in random number functions in Excel or Lotus 1-2-3. These functions, such as RAND in Excel, generate random numbers between 0 and 1 every time the spreadsheet is recalculated. Combined with macros, such functions can automatically run multiple scenarios without requiring specialized Monte Carlo analysis software.

Various software packages are available for constructing decision trees, ranging in cost from free to thousands of dollars. In addition, graphical decision trees and influence diagrams can be constructed from scratch in any graphic design program. Decision tree software has the advantage of built-in macros that allow automatic generation of probabilities. However, although such software can be used to build highly complex models with multiple uncertainties, their use becomes unwieldy very quickly. Decision tree software also tends to be oriented toward financial decision making and may be difficult to adapt to the complex performance metrics often needed to assess environmental sustainability decisions.

Most of the decision tree programs are add-ins for Excel or @RISK, enhancing these packages' functionality and allowing more formal decision trees. The primary advantage of a decision software package is the ease of constructing and presenting the tree. Some of these packages are described in the following list.

Occam's decision tree software. This program is one of the easiest to use. It allows the user to quickly add branches and optimize sub-nodes. A range of free templates can be used to tie it into Excel functions.

Lumenaut. This program provides a range of tools for constructing decision tree models within Excel. It also allows for sensitivity analysis and has effective graphics for representing information.

DPL. This is a common package with extensive modeling tools. It has multiple analysis components and is particularly easy to use for constructing relatively complex decision trees with one of the more simple interfaces.

Vanguard Studio. This standalone program is described as combining features of artificial intelligence, math applications, and spreadsheets. It has an effective wizard for creating the whole decision tree.

Palisade PrecisionTree. This Excel add-in integrates completely with spreadsheets. Precision Tree nodes, branches, and arcs are placed directly in a model, and values appear in the formula bar. The menu design and the toolbar make learning and navigating this software particularly easy.

The two common simulation software packages—@Risk and Crystal Ball—are very similar in framework and use. The basic elements of Crystal Ball are described in Chapter 13, in the discussion about constructing simulation models. In addition, basic aspects of decision tree software are explained, with examples using the PrecisionTree software. For an excellent step-by-step description of the use of @Risk software, see *Making Hard Decisions* by Clemen and Reilly (2001).

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CHAPTER

Case Study: Using Model Simulations to Define Woody Biomass for Renewable Energy Policy

11

William L. Hall

11.1 BASIC MODEL FRAMEWORK

A simple decision tree for establishing a policy definition for the use of woody biomass for renewable energy is illustrated in Figure 11.1. This decision tree represents a simplified version of a debate in Congress that occurred in the spring of 2009. The issue was the extent to which woody biomass should be considered eligible for renewable energy credits. A segment of the stakeholders in the wood product industry, primarily owners of forest land and rural communities, was advocating for a broad definition with limited constraints. They wanted to increase demand for cellulose mass through the creation of additional markets. In this case, if the regulations regarding renewable energy credits had a less restrictive definition of qualifying cellulose material, there was a greater likelihood that the cellulose-to-energy market would expand.

Traditional wood product users, primarily the pulp, paper, and lumber industries, were much less enthusiastic about competitive uses for their raw material streams. Environmental activists were more aligned with the pulp, paper, and lumber industry position, as they were concerned that too broad a definition would result in the mining of forests and the loss of biodiversity as slow-growth native hardwood forests were converted to pine plantations.

For the decision tree example in Figure 11.1, the alternative definitions for eligible cellulose biomass are simplified to three primary definitions:

- By-products or waste material (slag) only, which would make waste wood product materials alone eligible.
- All forest materials, which would be the most expansive definition, allowing any cellulose material to be eligible for credits.
- All forests materials but with three alternative specifications for special restrictions:
  1. Exclude all government-owned land—national forests and large tracts of land associated with military bases.

DOI: 10.1016/B978-1-85617-797-9.00011-3

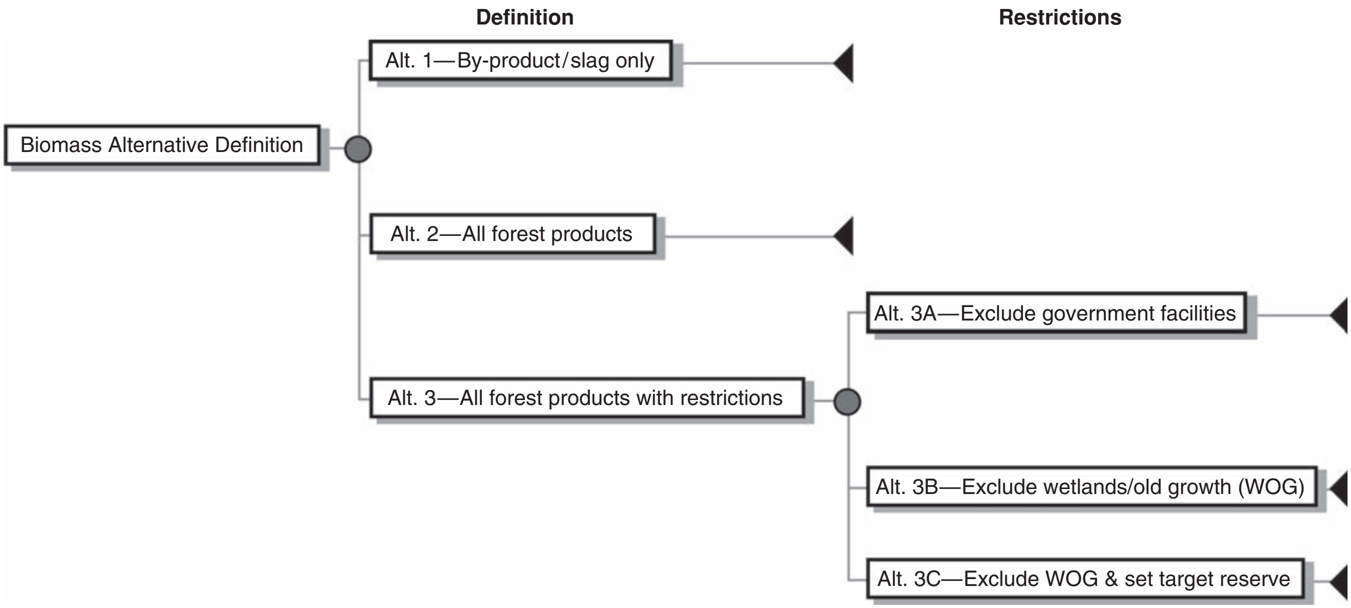


FIGURE 11.1

Simplified decision tree for renewable energy definition for cellulose biomass.

2. Exclude government tracts plus wetlands, old-growth forests, and special-designation forests (WOGS).
3. Exclude government tracts and WOGS, and set a minimum target for managed diversified forests.

To demonstrate the use of Oracle Crystal Ball, our case study is further simplified to examine only one objective at a smaller scale: forest preservation in the state of Georgia. Other objectives that could be examined include the impacts of alternatives on economic activity in specific counties, unemployment in rural Georgia, and environmental indicators such as habitat preservation. Depending on the ability of the decision makers to expand the scale of the decision context, objectives could include social indicators, such as civic integrity or community stability, and impact on health indicators associated with diversification of rural income streams.

The performance metric for the forest preservation objective is defined on the basis of quantity and relative quality of forest acreage likely under each alternative definition. Each definition of eligible biomass will create a change over the next 100 years in the number of acres kept as forest or converted to development, wetlands and old-growth forest preserved, and forest land managed for diversity.

An example of these outcomes is shown in Figure 11.2. The performance metric is developed from the assessment of the likely amount of forest land remaining after a 100-year planning period within three broad categories: pine plantation, wetland or old-growth forest, and managed diversified forest. The metric is an environmental indicator that weights the acreage depending on the forest type.

11.2 INCORPORATING UNCERTAINTY

The next step in the process is to capture the uncertainty associated with each input. For example, the likely loss of forest land to development is not a fixed estimate but a range. The simplest approach is to identify likely conversions based on available knowledge of past development patterns and expected growth rates expected by government agencies.

Assume that land conversion in Georgia in a given year ranged from an average of 25 to 150 acres per day over the past 30 years. Using those numbers, the loss of acreage over 100 years would range from only about 5 percent at the lower end to 30 percent at the upper end. A variety of distribution types (curves) are available to express this range in the Crystal Ball software gallery of choices. A few of these are shown in Figure 11.3. A description of the more commonly used distributions is provided in Figure 11.4.

An example of distributions for alternative 1 variable inputs is shown in Figure 11.5 (see page 223). A BetaPERT distribution is used to define the expected distribution of the rate at which land is converted from forest or open space to

Woodland Relative Value				
Total Woodland Acreage (Millions)	Pine Plantation	Managed Mixed Forest	WOGs	Passive Use Land
26	0.5	0.75	1	0.6

Alternative	Available for Biomass (Millions of Acres)	Likely Loss of Total Acreage to Development	% Pine Plantation	% Managed Mixed Forest	Wetlands and Old Growth (WOGs)	Forest Land in 2110	Environmental Indicator
Alt. 1	**8**	**30%**	**50%**	**5%**	**2.5%**	**18.2**	**13.4225**
Alt. 2	**22**	**10%**	**60%**	**10%**	**5%**	**23.4**	**14.4950**
Alt. 3A	**19**	**17.5%**	**60%**	**10%**	**5%**	**21.45**	**13.6663**
Alt. 3B	**18**	**10%**	**50%**	**10%**	**7.5%**	**23.4**	**15.2750**
Alt. 3C	**15**	**20%**	**40%**	**20%**	**10%**	**20.8**	**14.7550**

FIGURE 11.2

Performance metrics for forest environmental indicators.

development, as well as the expected amount of land with each forest type after 100 years. Figure 11.6 illustrates the next step of determining the performance metric distribution: assigning a relative value to each forest type.

Figure 11.7 indicates the change in input values and in the predicted performance metric value for the quality of woodlands after 100 years for individual simulations (see page 225). Two distinct simulations are shown. Each results in a unique set of values chosen by the Monte Carlo technique described in Chapter 10, and each produces a distinct prediction of the performance metric value.

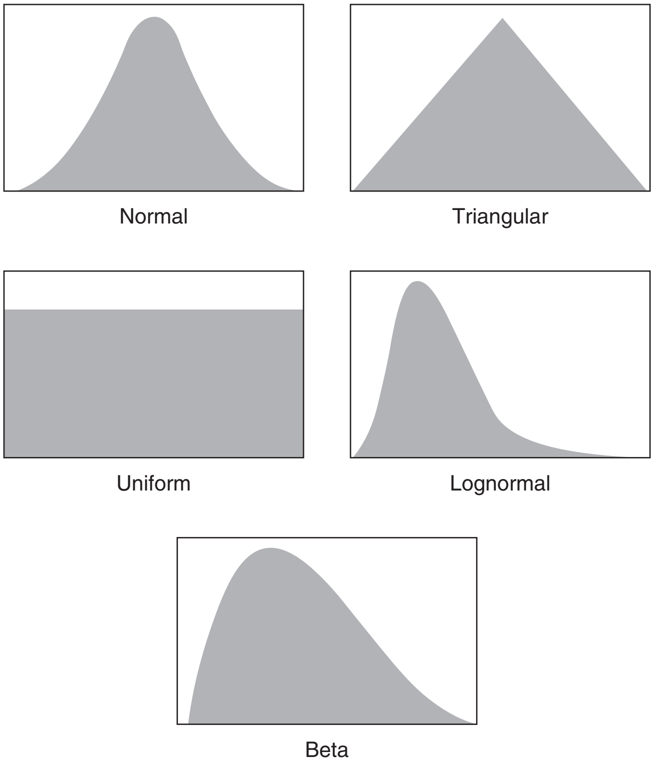


FIGURE 11.3

Some of the distributions available in Crystal Ball software.

Figure 11.8 shows the distribution of predictions for the performance metric for alternative 1 over the course of 1,000 individual simulations. For the particular set of uncertainty assumptions, the performance metric value ranges from 8.43 to 11.21 million diversified forest equivalency acres. These numbers represent a weighted acreage equivalency based on the relative value of the forest type. In the example shown in Figures 11.5 through 11.8 (see pages 223–226), a pine plantation is assigned 30 to 50 percent of the value of a wetland/old-growth/special-reserve forest.

Additional refinements to the estimate of outcomes can be achieved, principally through the disaggregation of uncertainties and through sequential uncertainties, as discussed in the following sections.

11.3 DISAGGREGATING UNCERTAINTIES

Section 11.2 describes the distribution of input variables for the conversion of land to development and the mixture of forest types developed using knowledge of past conversion rates and use patterns. The past informs decision makers on some of the

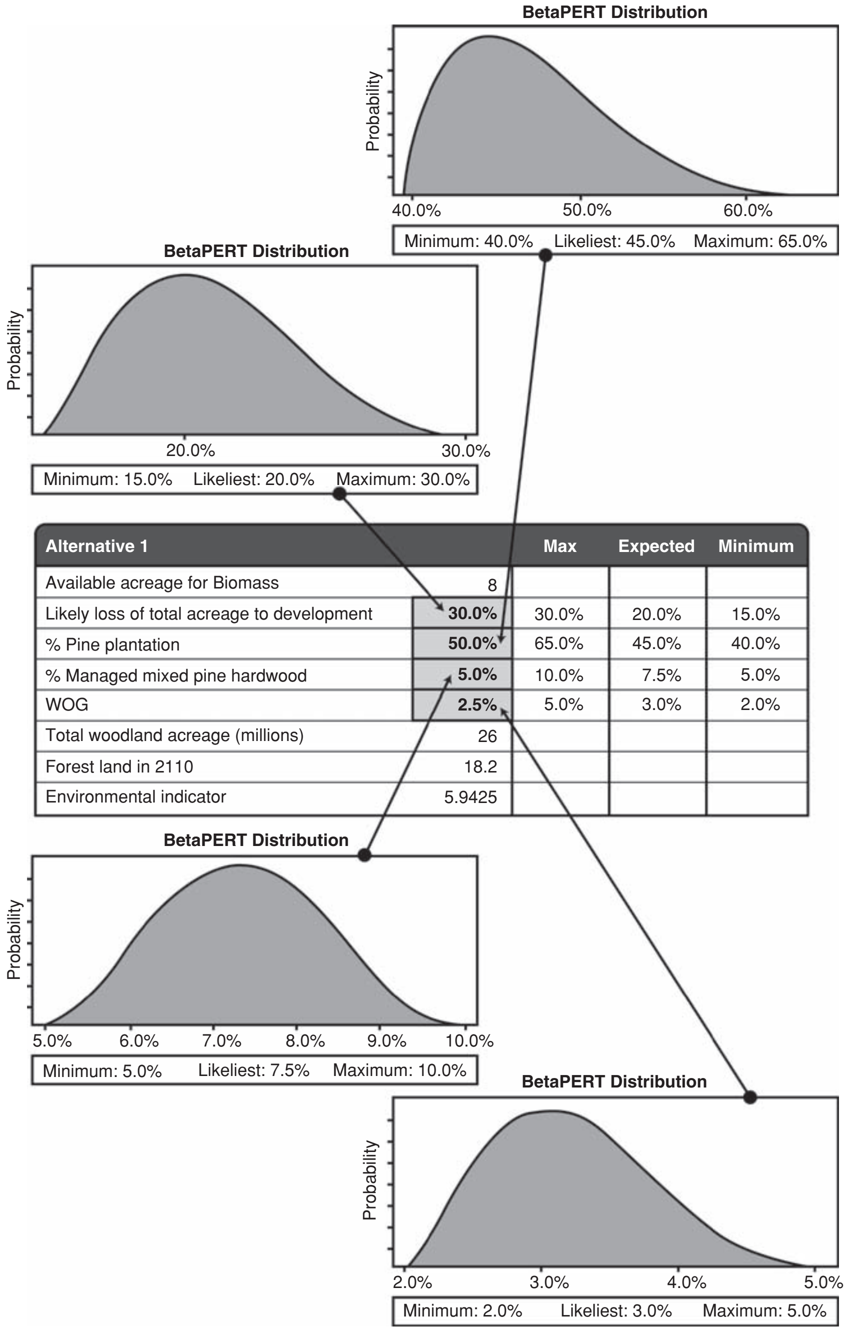
Normal Distribution — The normal distribution describes many natural phenomena such as the distribution of a particular physical characteristic of a population.
Uniform Distribution — A uniform distribution is one in which all values between the minimum and maximum are equally likely to occur.
Lognormal Distribution — The lognormal distribution is appropriate where most of the potential outcomes occur near the minimum value. This would apply in an estimate of land conversion rates in a community in which land development could occur at 7% or 8%, but the likely long-term growth rates cluster around 1% to 3%.
Beta Distribution — The beta distribution is a flexible distribution for modeling probabilities based on Bayesian statistics. It is particularly useful when there is empirical data available for curve fitting to observed phenomenon.
Gamma Distribution — The gamma distribution applies to a wide range of physical quantities. Examples include meteorological processes to represent pollutant concentrations and precipitation quantities.
Maximum Extreme of Gumbel Distribution — The Gumbel distribution can be used to describe the largest value of a response over a period of time such as flood flows, rainfall, heat island effect, loss of habitat, and so on.
Logistic Distribution — The logistic distribution is commonly used to describe growth.
Student's Distribution — The distribution is similar to a normal curve but with more outliers and more concentration in the central region. As the number of samples (degrees of freedom) increases, the distribution approximates the normal distribution, with the two being indistinguishable at 30 degrees of freedom.
Exponential Distribution — The exponential distribution is particularly useful for defining the rate of change of environmental parameter that is undergoing biological or chemical decay or conversion.
BetaPERT Distribution — The BetaPERT distribution is used as a "smoother" alternative to the triangular distribution.

FIGURE 11.4

Descriptions of distributions.

possible outcomes, but it does not dictate the trajectory of what might happen in the years to come. Still, it is possible to break down an uncertainty into the forcing functions that may affect the trajectory of future events. These forcing functions can then be examined individually, allowing more control and focus for the analysis.

Analysis of one of the uncertainties—forest conversion to development—demonstrates the disaggregation of an uncertainty. Three policy issues in



Alternative 1		Max	Expected	Minimum
Available acreage for Biomass	8			
Likely loss of total acreage to development	**30.0%**	30.0%	20.0%	15.0%
% Pine plantation	**50.0%**	65.0%	45.0%	40.0%
% Managed mixed pine hardwood	**5.0%**	10.0%	7.5%	5.0%
WOG	**2.5%**	5.0%	3.0%	2.0%
Total woodland acreage (millions)	26			
Forest land in 2110	18.2			
Environmental indicator	5.9425			

FIGURE 11.5

Performance metrics for forest environmental indicators.

Alternative 1		Max	Expected	Minimum
Available Acreage for Biomass	8			
Likely Loss of Total Acreage to Development	**30%**	30%	20%	15%
% Pine Plantation	**50%**	65%	45%	40%
% Managed Mixed Pine Hardwood	**5%**	10%	7.5%	5%
WOG	**2.5%**	5%	3%	2%
Total Woodland Acreage (millions)	26			
Forest Land in 2110	18.2			
Environmental Indicator	5.9425			

Woodland Relative Value		Max	Expected	Minimum
Pine Plantation	**0.5**	50%	40%	30%
Managed Diversified Forest	**0.75**	90%	80%	70%
WOG	**1**	100%	90%	85%
Passive Use Land	**0.6**	70%	60%	40%

FIGURE 11.6

Performance metrics for woodland relative value.

Simulation 1

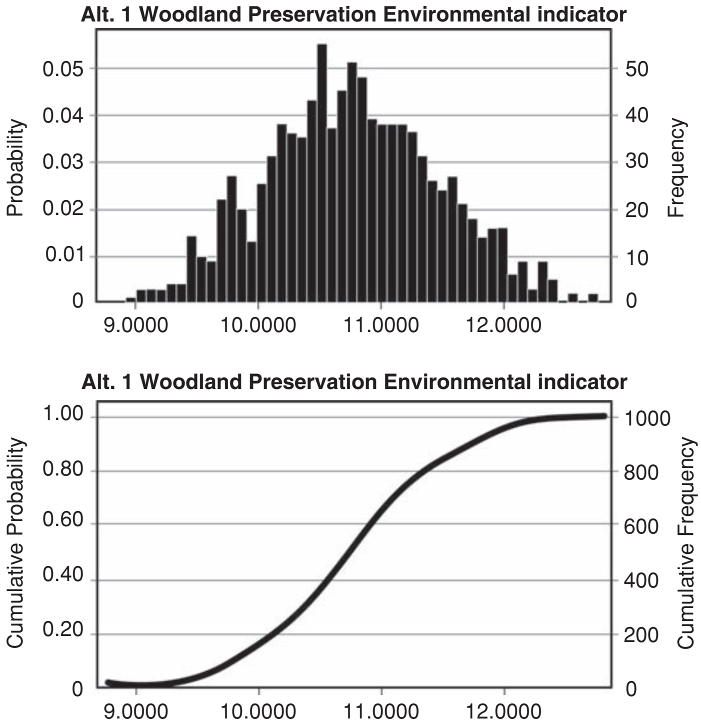
Alternative 1		**Max**	**Expected**	**Minimum**
Available Acreage for Biomass	8			
Likely Loss of Total Acreage to Development	30.0%	30.0%	20.0%	15.0%
% Pine Plantation	50.0%	65.0%	45.0%	40.0%
% Managed Mixed Pine Hardwood	5.0%	10.0%	7.5%	5.0%
WOG	2.5%	5.0%	3.0%	2.0%
Total Woodland Acreage (Millions)	26			
Forest Land in 2110	18.2			
Woodland Preservation Environmental Indicator	**10.3285**			
Woodland Relative value		**Max**	**Expected**	**Minimum**
Pine Plantation	0.50	50.0%	40.0%	30.0%
Managed Diversified Forest	0.75	90.0%	80.0%	70.0%
WOG	1.00	100.0%	90.0%	85.0%
Passive Use Land	0.60	70.0%	60.0%	40.0%

Simulation 2

Alternative 1		**Max**	**Expected**	**Minimum**
Available Acreage for Biomass	8			
Likely Loss of Total Acreage to Development	20.4%	30.0%	20.0%	15.0%
% Pine Plantation	42.8%	65.0%	45.0%	40.0%
% Managed Mixed Pine Hardwood	7.2%	10.0%	7.5%	5.0%
WOG	3.2%	5.0%	3.0%	2.0%
Total Woodland Acreage (Millions)	26			
Forest Land in 2110	20.68988739			
Woodland Preservation Environmental Indicator	**9.4981**			
Woodland Relative value		**Max**	**Expected**	**Minimum**
Pine Plantation	0.32	50.0%	40.0%	30.0%
Managed Diversified Forest	0.78	90.0%	80.0%	70.0%
WOG	0.95	100.0%	90.0%	85.0%
Passive Use Land	0.51	70.0%	60.0%	40.0%

FIGURE 11.7

Performance metrics for woodland relative value.



Forecast:

Statistic	Forecast values
Trials	1,000
Mean	10.7655
Median	10.7565
Standard Deviation	0.7161
Minimum	8.4300
Maximum	13.2146
Mean Std. Error	0.0226

FIGURE 11.8

Woodland preservation performance metric for alternative 1.

conjunction with one macro issue could radically alter the trajectory based on past development growth rates:

- Transportation
- Land use
- Energy
- National economic trends

The actual impact of such policy issues cannot be precisely defined, especially given the inevitable unintended consequences despite the best of intentions. However, it is possible to establish a range of how the trajectory of land conversion from the past will be altered based on public policy regarding transportation, land use, and energy use. Serious efforts to alter societal behavior through policies that foster sustainability will slow the rate of resource consumption, if not actually reverse the trends.

Figures 11.9 through 11.11 illustrate the use of Palisade® PrecisionTree to calculate the impact of policy on land conversion rate. The steps shown in each figure are described in the following subsections.

Step 1: Defining Disaggregated Uncertainties, Probabilities, and Values

Step 1 defines the uncertainties (i.e., possible outcomes), the probability of each outcome, and the values associated with each outcome. Figure 11.9 shows the disaggregation of the uncertainties. For each policy the outcomes are simplified to two distinct policy directions. One is a proactive move toward sustainability that internalizes costs and benefits for resource use. The alternative branch for each uncertainty is a continuing reactive approach to resource-mining problems.

Figure 11.10 shows that the values are the percent reductions in the rate at which land was converted to development in the past. The inputs themselves can be variables, as shown in Figure 11.11. In this example, the political climate of a strongly conservative state with aggressive pro-growth policies is not conducive to proactive sustainability. Decision makers must take into account the political reality that will affect the consequences. However, broader national trends, external pressures, the growing percentage of voters under 30, and changes in power balances could produce public pressures that currently seem unlikely and that were not at play in the past. For each uncertainty, then, a range of probabilities for the adoption of sustainability policies is used.

As with the range of probabilities for adoption of sustainability policies, the actual impact of a policy change is an obvious uncertainty. For example, transportation policy that deemphasizes government subsidies and enablement of suburban sprawl may or may not have a dramatic impact. The impact may be quite modest if hub-and-spoke mass transit continues to allow sprawl to occur around even more far-flung towns and villages. Mass transit–focused systems could even have the unintended consequence of encouraging development in the countryside even as the cost of energy increases.

Step 2: Defining the Interaction of Uncertainties

In our example, the policies are at least partially independent. Their combined impacts can take several forms, ranging from cumulative to averaged. If completely independent, for example, the impacts would be cumulative. In this situation, individual reduction in conversion rates would be multiplicative. In other words, a transportation policy that produced a rate of forest land conversion

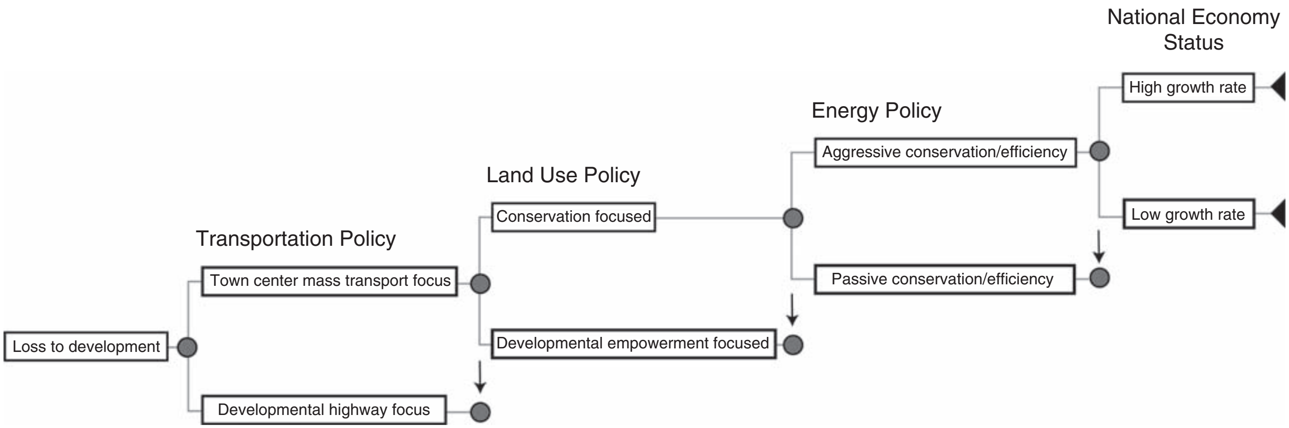


FIGURE 11.9

Disaggregation of uncertainty of loss of woodland to development. The uncertainty tree is symmetrical, meaning that the nodes are the same along each branch.

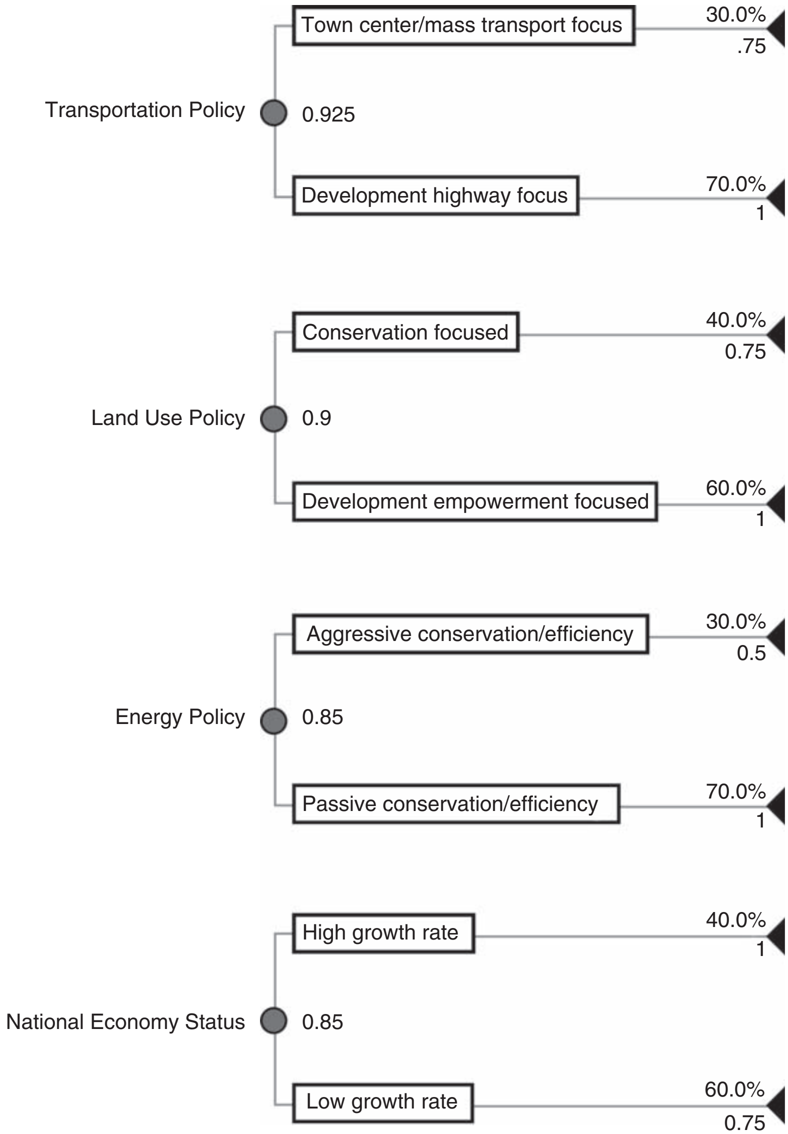


FIGURE 11.10

Step 1: Assignment of probabilities and values to disaggregated uncertainty of loss of woodland to development.

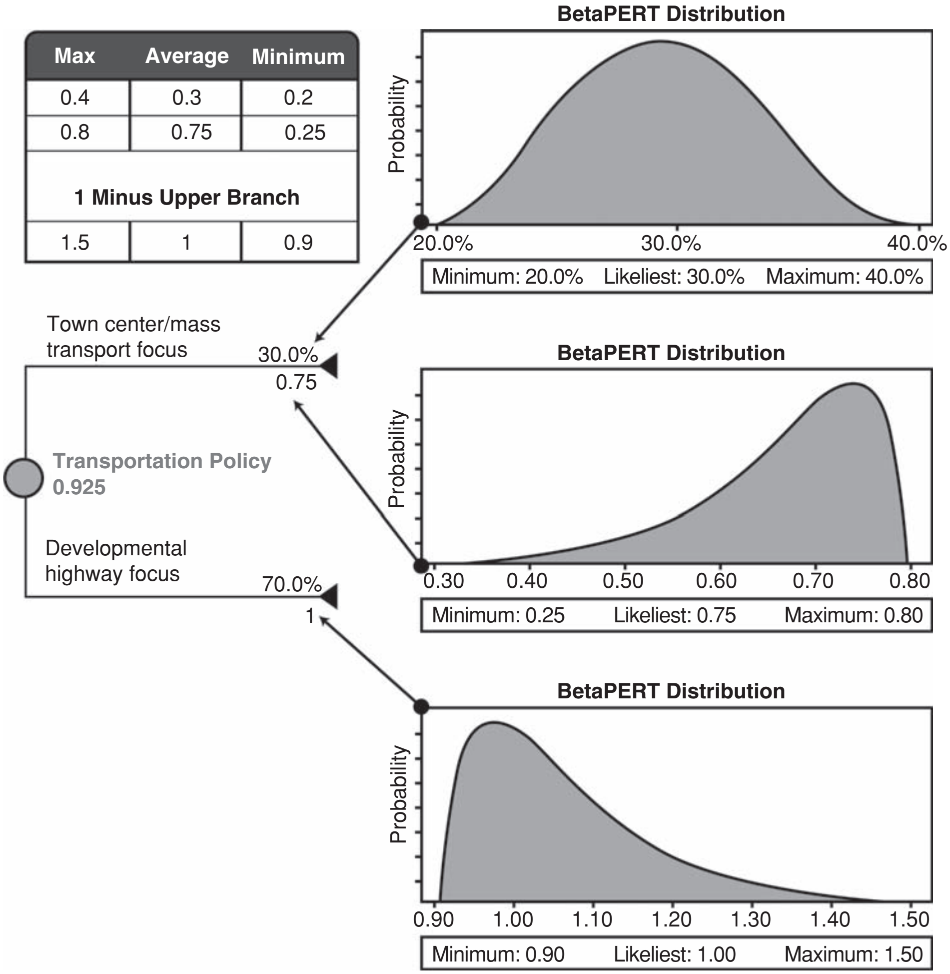


FIGURE 11.11

Step 1: Example distributions for disaggregated uncertainty of loss of woodland to development-transportation policy impacts.

that is 75 percent of the past rate would be multiplicative with a land use policy that produced a 50 percent reduction in the conversion rate. The net reduction in the land conversion rate would then be $0.75 \times 0.5 = 0.375$.

In actuality, the impacts of the different policies are not additive but overlapping. Depending on the particular combination of policies, the overlap may be mutually supportive or self-canceling. Figure 11.12 demonstrates an approach for combining the impacts of two policies: transportation and land use. Based on

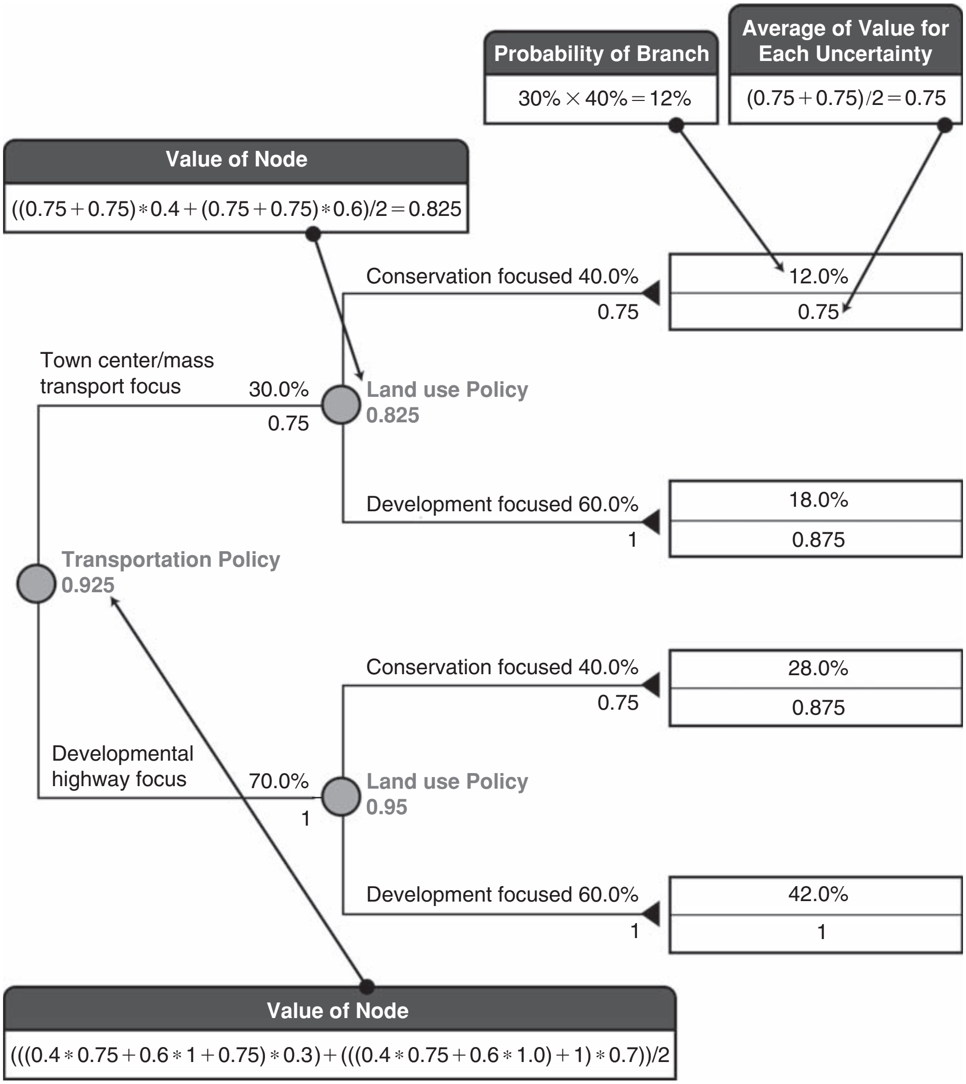


FIGURE 11.12

Step 2 defines the interaction of individual nodes of disaggregated uncertainty for the loss of woodland to development.

the initial limit of two possible outcomes—sustainability or pro-growth—four classes of outcomes are possible in this case:

- Sustainability-based policies for both transportation and land use
- Sustainability-based policies for transportation but not land use

- Sustainability-based policies for land use but not transportation
- Pro-growth policies for both transportation and land use

The figure also demonstrates the calculation of the value of each node, the probability and value of each branch, and the calculated value for the change in the trajectory of land conversion. In our example the value is calculated as the average change between the two policies. The branches are calculated moving from left to right, adding the values and dividing by 2. The probabilities for each branch are multiplicative. The values of the nodes are calculated moving from right to left.

Step 3: Constructing an Uncertainty Tree for the Interaction of Disaggregated Uncertainties

Figures 11.13 and 11.14 show the completed uncertainty tree. The tree captures the interaction of the policy uncertainties that could alter the rate at which forest land had been converted to developed property in the past. Each uncertainty provides one-half of the tree. The example is simplified by assuming that the tree is completely symmetrical (i.e., no matter which way an uncertainty branches, the next decision is the same). In addition, it is greatly simplified in that each policy issue can only move in two directions—toward sustainability or development. Variability in the consequences of the policy direction is captured by varying the potential impact.

The tree can be refined by identifying more specific policy strategies. As is obvious from the size of a simple tree with only four nodes and two branches, adding additional branches can quickly create an analysis framework that is unwieldy and unworkable. The effectiveness of an analysis is highly dependent on balancing the level of uncertainty disaggregation with the need for a manageable analysis framework.

Step 4: Generating Factors for Disaggregated Uncertainties

Factors can be generated that capture the disaggregated uncertainties, as illustrated in Figure 11.15, which shows the result of a Monte Carlo analysis of the uncertainty tree of Figures 11.13 and 11.14. This factor adjusts the variable for the rate of forest conversion provided earlier in Figure 11.6. It takes into account the impact various policies can have on the likely rate of future forest land conversion, instead of merely measuring the past rate of conversion.

11.4 SEQUENTIAL UNCERTAINTIES

Sequential uncertainties are contingent on the decision and affect the consequences. Decision makers have some control over the uncertainties that follow from a specific decision. The example shown in Figure 11.16 (see page 236)

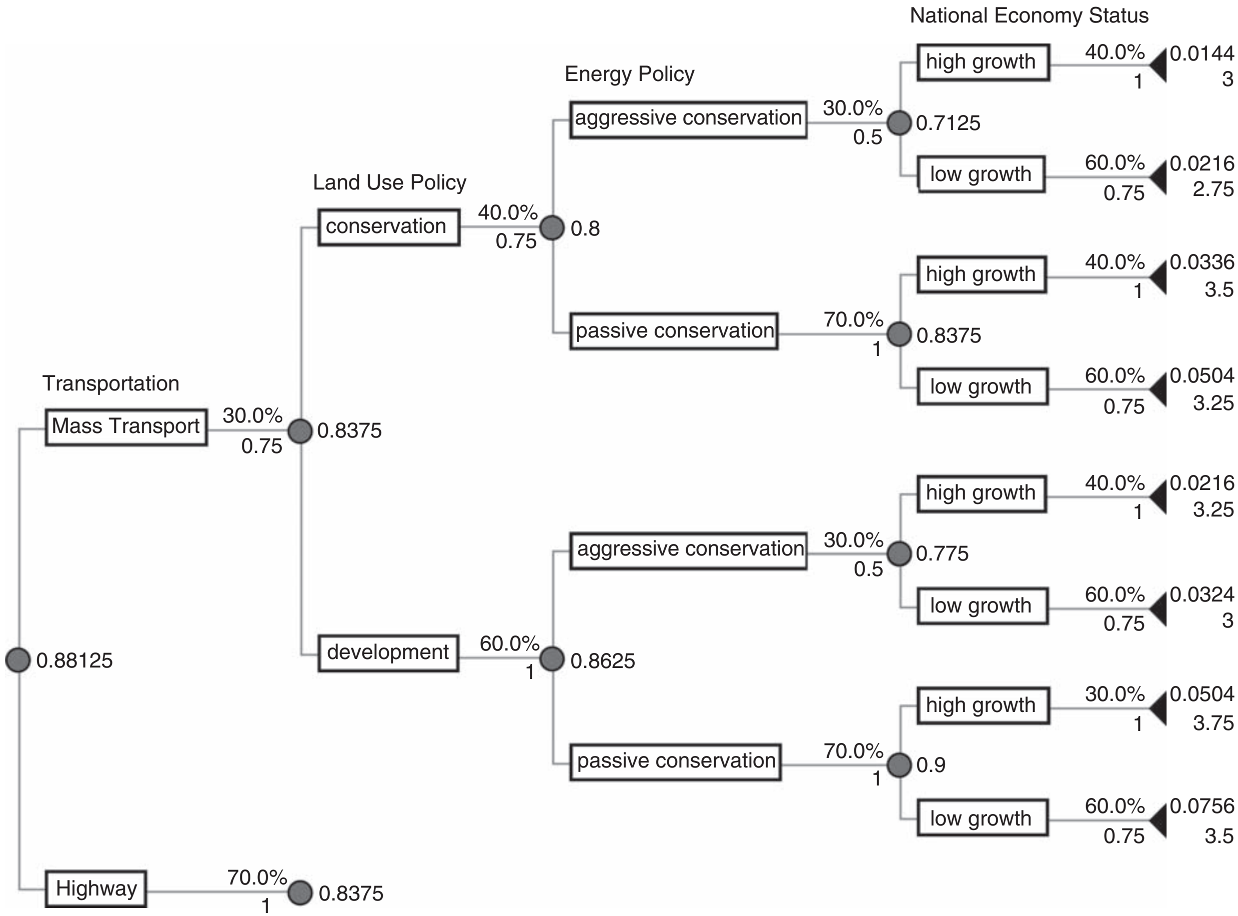


FIGURE 11.13

Step 3: Construction of uncertainty tree for the interaction of four policy uncertainties affecting loss of woodland to development—top half.

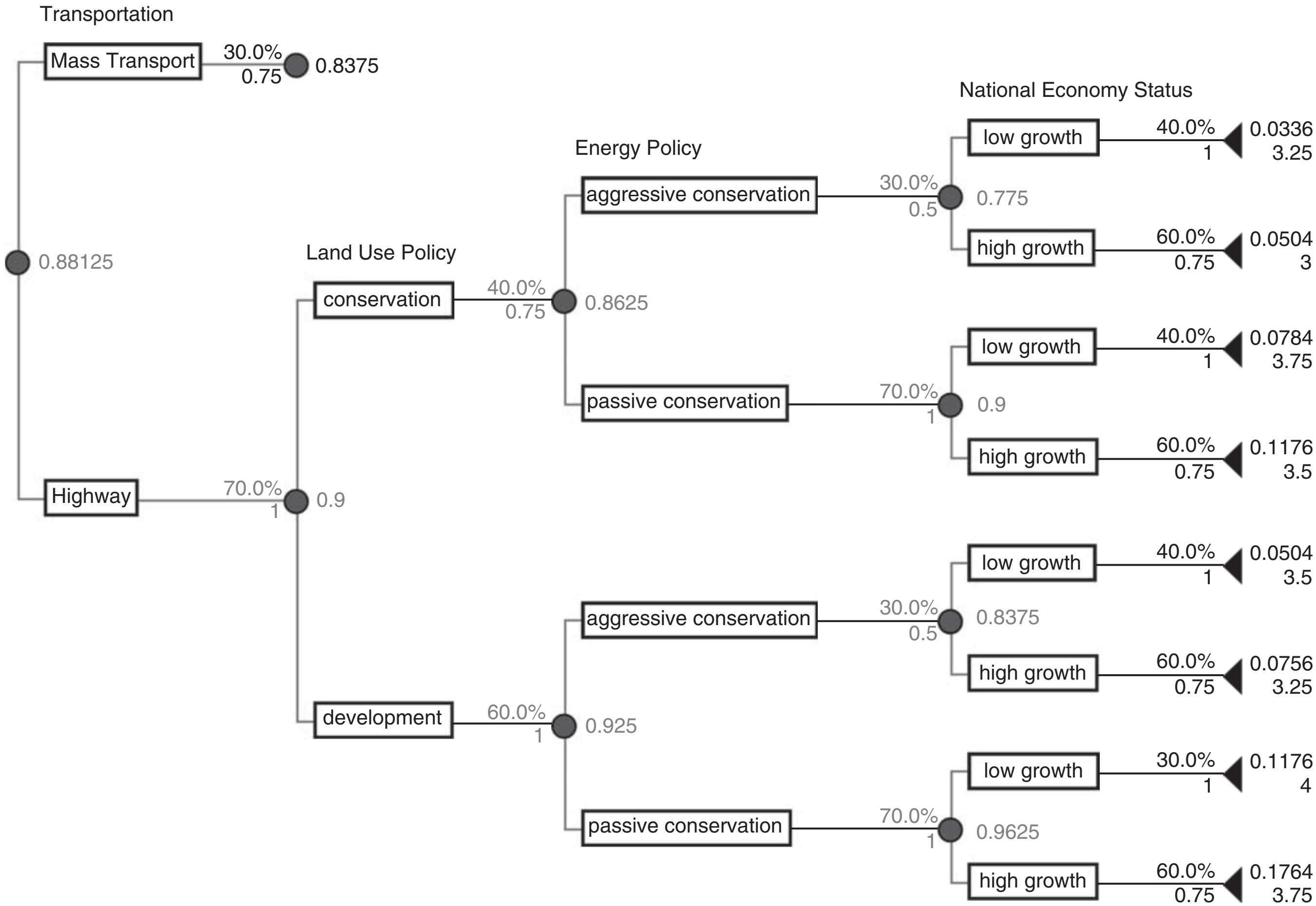
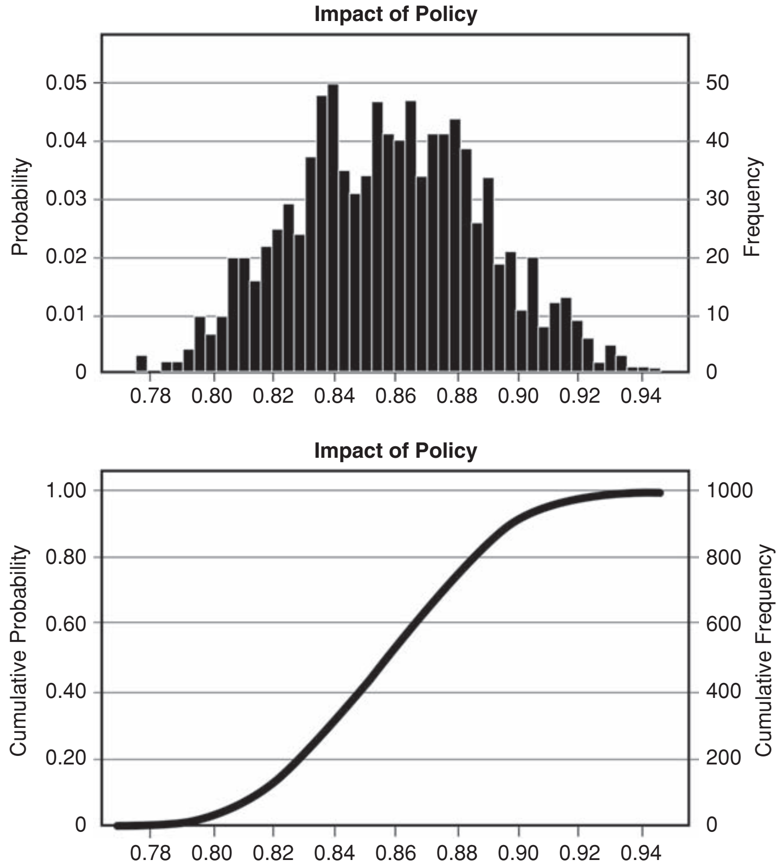


FIGURE 11.14

Step 3: Construction of uncertainty tree for the interaction of four policy uncertainties affecting loss of woodland to development—bottom half.



Forecast:

Statistic	Forecast values
Trials	1,000
Mean	0.86
Standard Deviation	0.03
Minimum	0.76
Maximum	0.96

FIGURE 11.15

Impact of policy on rate of conversion of forest lands to development.

revisits the definition of renewable energy with respect to wood products. To prevent the unintended consequences of forest mining, it is assumed that the definition is coupled with constraints and incentives for preservation of diversified forests. However, the policy is defined sequentially, meaning that the definition of allowable biomass is selected before the guidelines for forest preservation are finalized.

This type of situation can be readily handled using the Crystal Ball software in Microsoft Excel. It involves using "if-then" statements, which select different

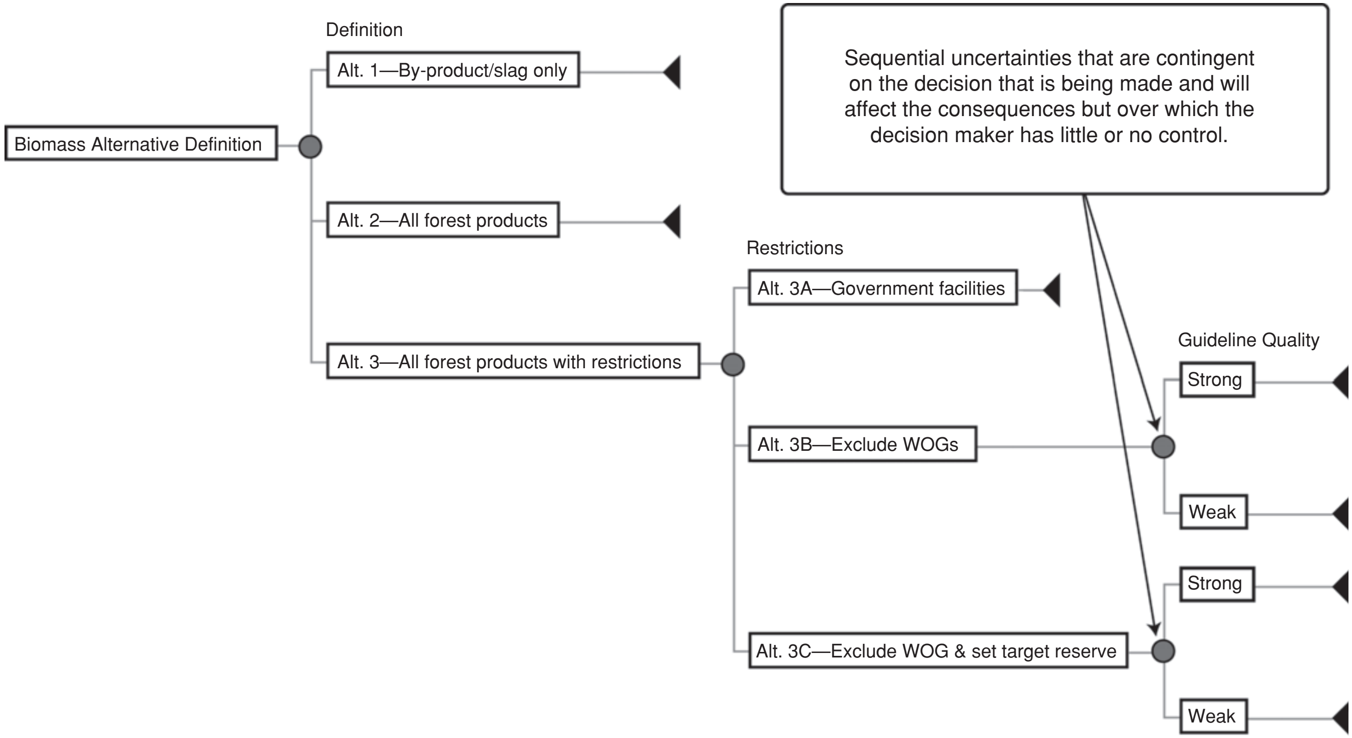


FIGURE 11.16

Example of sequential uncertainties.

probability distributions for the outcomes of subsequent uncertainties depending on the outcomes of prior uncertainties. In our example, the quality of the guidelines affects the quality of the wetlands and old-growth and diversified forests, as well as the relative percentage of forest lands eventually preserved. If we assume that there is a 50 percent chance of obtaining strong guidelines, in the Monte Carlo assessment 50 percent of the simulations will select a distribution based on obtaining strong guidelines for diversified forest preservation. Conversely, 50 percent will use a distribution based on weak guidelines. Figure 11.17 provides the data involved in the IF function to address a sequential uncertainty.

The flexibility of the Crystal Ball software permits a variety of assessments of alternative directions due to sequential uncertainties. For example, rather than building in a fixed value of 50 percent, decision makers could treat the probability of weak or strong regulations itself as a variable simulated through Monte Carlo analysis.

11.5 SIMULATION RESULTS

Example simulation results are shown in Figures 11.18 through 11.22. Figures 11.19 and 11.20 provide examples of single simulations. They demonstrate how Monte Carlo simulation selects values from the distributions shown in Figure 11.18 to populate the simulation matrix. The output is the performance metric in the last column of Figures 11.19 and 11.20. The performance metric for the objective of woodland preservation is the woodland acreage, weighted to take into account the relative value of different types of woodland, from pine plantation to wetlands to managed mixed pine/hardwood forests.

Figures 11.21(a, b, and c) show the results of the distribution of performance metric prediction for 1,000 simulations. Figure 11.21(a) shows the performance metric frequency distributions for each alternative (see page 242). Figure 11.21(b) shows the cumulative curves for the five distributions shown in Figure 11.21(a). Figure 11.21(c) shows the trend curves for the five distributions.

The benefits of different graphical representations were explained in Chapter 10. Each curve provides a different graphical tool for displaying the relative consequences of the five alternatives. Graphical tools allow decision makers to understand the relative likely outcomes in quantitative terms defined specifically for the decision setting at hand. However, it should be stressed that the information they provide is not static and does not provide the answer. Rather, the simulation results provide a means for decision makers to comprehensively assess likely consequences based on their best judgment of the uncertainties' characteristics. After the simulation model is constructed, decision makers have a tool for iteratively examining uncertainties, observing likely consequences, and testing assumptions.

Woodland Relative Value—Strong Guidelines		Max	Expected	Minimum
% Pine Plantation	50.0%	50.0%	40.0%	30.0%
% Managed Mixed Forest	75.0%	90.0%	80.0%	70.0%
% WOG	100.0%	100.0%	90.0%	85.0%
% Passive Use Land	60.0%	70.0%	60.0%	40.0%

Woodland Relative Value—Weak Guidelines		Max	Expected	Minimum
% Managed Mixed Forest	60.0%	75.0%	60.0%	50.0%
% Passive Use Land	50.0%	65.0%	50.0%	40.0%

Guideline Counter		Yes/No
Strong—Yes	50.0%	100%
Weak—No	50.0%	

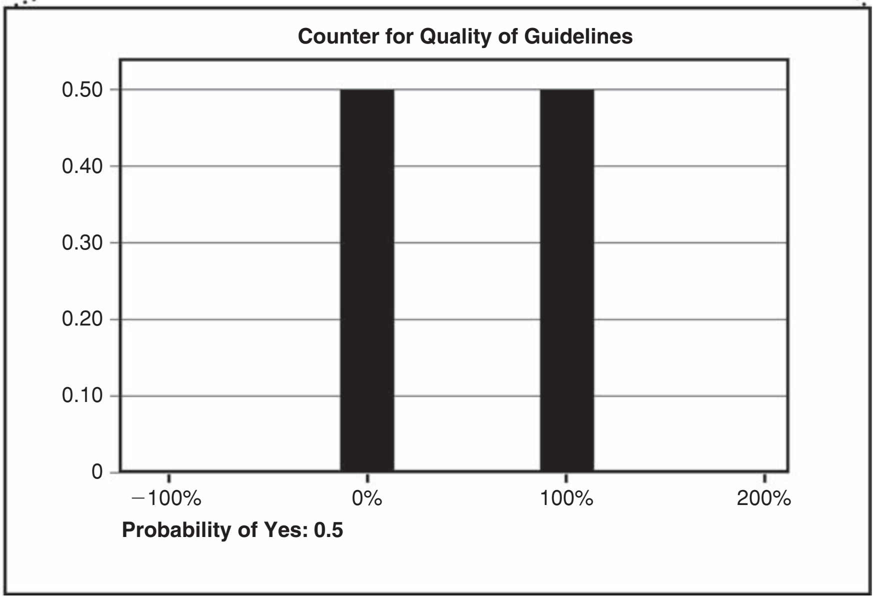


FIGURE 11.17

Use of YES/NO distribution and/or IF statement to select among alternative distributions.

Alternative 1—By-Product Slag Only		Max	Expected	Minimum
Likely Loss of Total Acreage to Development	**30.0%**	30.00%	20.0%	15.0%
% Pine Plantation	**50.0%**	65.00%	45.0%	40.0%
% Managed Mixed Pine Hardwood	**5.0%**	10.00%	7.5%	5.0%
% WOG	**2.5%**	5.00%	3.0%	2.0%
Alternative 2—All Forest Product		**Max**	**Expected**	**Minimum**
Likely Loss of Total Acreage to Development	**12.5%**	30.0%	12.5%	10.0%
% Pine Plantation	**60.0%**	65.0%	60.0%	40.0%
% Managed Mixed Pine Hardwood	**10.0%**	10.0%	10.0%	5.0%
% WOG	**5.0%**	5.0%	5.0%	2.0%
Alternative 3A—Restricted Government Facilities		**Max**	**Expected**	**Minimum**
Likely Loss of Total Acreage to Development	**17.5%**	25.0%	17.5%	15.0%
% Pine Plantation	**60.0%**	65.0%	60.0%	40.0%
% Managed Mixed Pine Hardwood	**10.0%**	15.0%	10.0%	5.0%
% WOG	**5.0%**	7.5%	5.0%	3.0%
Alternative 3B—Restricted WOGS		**Max**	**Expected**	**Minimum**
Likely Loss of Total Acreage to Development	**10.0%**	15.0%	10.0%	7.5%
% Pine Plantation	**50.0%**	60.0%	50.0%	40.0%
% Managed Mixed Pine Hardwood	**10.0%**	12.5%	10.0%	5.0%
% WOG	**7.5%**	10.0%	7.5%	5.0%
Alternative 3A—Restricted WOGs & Target Preservation		**Max**	**Expected**	**Minimum**
Likely Loss of Total Acreage to Development	**20.0%**	15.0%	10.0%	7.5%
% Pine Plantation	**40.0%**	55.0%	40.0%	35.0%
% Managed Mixed Pine Hardwood	**20.0%**	25.0%	20.0%	15.0%
% WOG	**10.0%**	12.5%	10.0%	5.0%

Woodland Relative Value—Strong Guidelines		Max	Expected	Minimum
% Pine Plantation	**50.0%**	50.0%	40.0%	30.0%
% Managed Mixed Forest	**75.0%**	90.0%	80.0%	70.0%
% WOG	**100.0%**	100.0%	90.0%	85.0%
% Passive Use Land	**60.0%**	70.0%	60.0%	40.0%
Woodland Relative Value—Weak Guidelines		**Max**	**Expected**	**Minimum**
% Managed Mixed Forest	**60.0%**	75.0%	60.0%	50.0%
% Passive Use Land	**50.0%**	65.0%	50.0%	40.0%

Guidelines Counter		Yes/No
Strong—Yes	**50.0%**	100%
Weak—No	**50.0%**	

FIGURE 11.18

Input Data for Monte Carlo simulation of woodland preservation performance metric.

Simulation Table—Simulation 1							
	Available for Biomass (Millions of Acres)	**Likely Loss of Total Acreage to Development**	**% Pine Plantation**	**% Managed Mixed Forest**	**Wetlands, Old Growth, & Special Reserves (WOGS)**	**Forest Land in 2110 (Millions of Acres)**	**Environmental Indicator**
Alternative 1 Waste Only	8	14.6%	43.1%	7.9%	3.6%	22.20	**12.31**
Alternative 2 Expansive/Limited Restrictions	22	12.7%	57.9%	9.8%	4.7%	22.71	**12.24**
Alternative 3A Expansive without Government Facilities	19	15.4%	63.2%	9.5%	4.9%	21.98	**11.73**
Alternative 3B Expansive with WOGS Restrictions	18	8.2%	53.6%	9.6%	8.4%	23.86	**12.88**
Alternative 3C Expansive with WOGS & Guideline Restrictions	15	9.7%	39.3%	18.7%	8.9%	23.48	**13.03**

Woodland Relative Value				
Total Woodland Acreage (Millions)	**Pine Plantation**	**Managed Mixed Forest**	**WOGs**	**Passive Use Land**
26	0.5	0.61	0.51	0.6

Disaggregated Uncertainty	
Policy impact on likely loss of total acreage to development	0.87

Sequential Uncertainty	
Weak/strong forest protection guidelines	WEAK

FIGURE 11.19

Example single simulation of performance metrics (woodland preservation environmental indicator).

Simulation software packages such as Crystal Ball provide a variety of tools for examining the sensitivity of different assumptions. Sensitivity analysis graphs can provide a starting point for exploring critical uncertainties more deeply (see Figure 11.22 on page 243). Most important, they provide a way for a group of potentially diverse decision makers to comprehensively examine the interaction of assumptions and uncertainties.

Simulation Table—Simulation 2	Available for Biomass (Millions of Acres)	Likely Loss of Total Acreage to Development	% Pine Plantation	% Managed Mixed Forest	Wetlands, Old Growth, & Special Reserves (WOGS)	Forest Land in 2110 (Millions of Acres)	Environmental Indicator
Alternative 1 Waste Only	8	24.9%	47.2%	8.5%	2.6%	19.53	**11.14**
Alternative 2 Expansive/Limited Restrictions	22	9.4%	59.1%	8.4%	4.4%	23.57	**13.17**
Alternative 3A Expansive without Government Facilities	19	14.2%	59.0%	10.6%	4.9%	22.30	**12.56**
Alternative 3B Expansive with WOGS Restrictions	18	10.3%	53.8%	9.9%	7.4%	23.33	**13.24**
Alternative 3C Expansive with WOGS & Guideline Restrictions	15	11.1%	40.9%	17.7%	11.0%	23.10	**13.79**

Woodland Relative Value

Total Woodland Acreage (Millions)	Pine Plantation	Managed Mixed Forest	WOGs	Passive Use Land
26	0.5	0.81	0.61	0.6

Disaggregated Uncertainty

Policy impact on likely loss of total acreage to development	0.89

Sequential Uncertainty

Weak/strong forest protection guidelines	STRONG

FIGURE 11.20

Example of a single simulation of the performance metrics (woodland preservation environmental indicator).

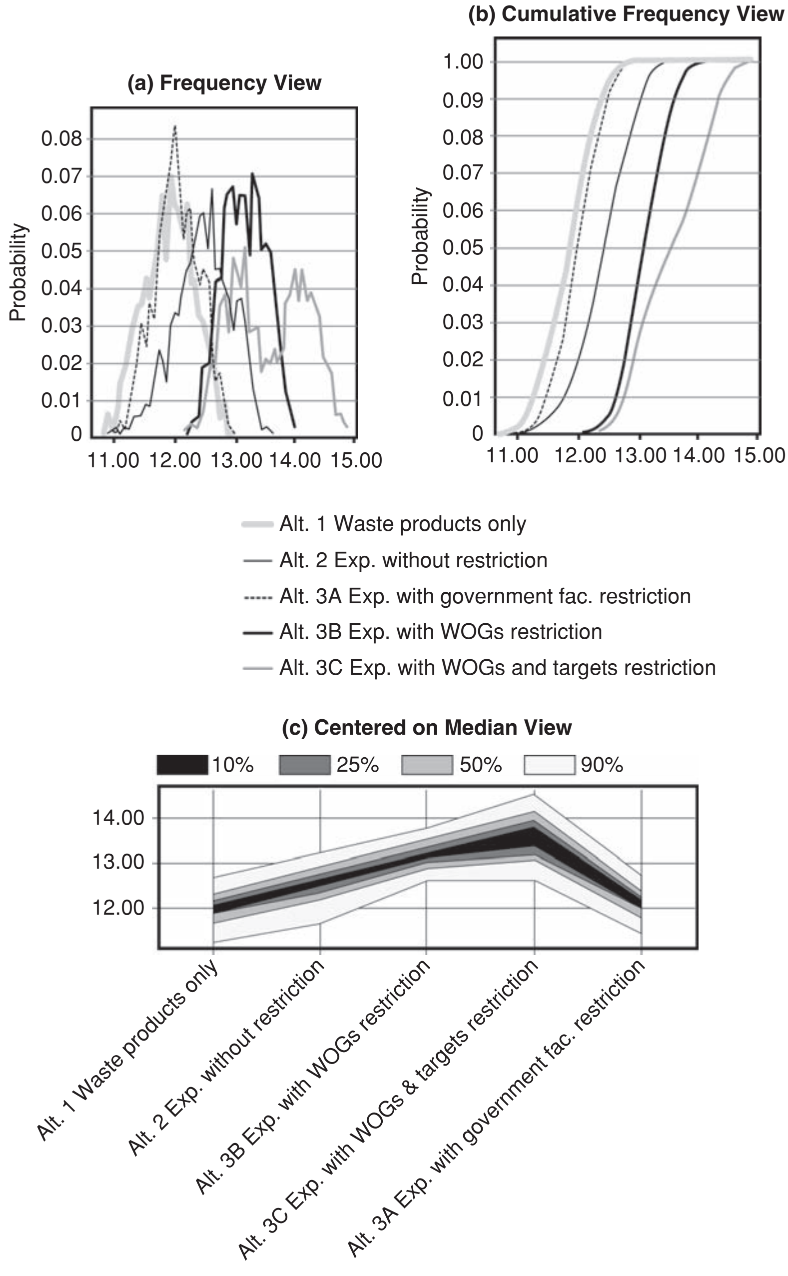


FIGURE 11.21

Simulation results for woodland preservation performance metric.

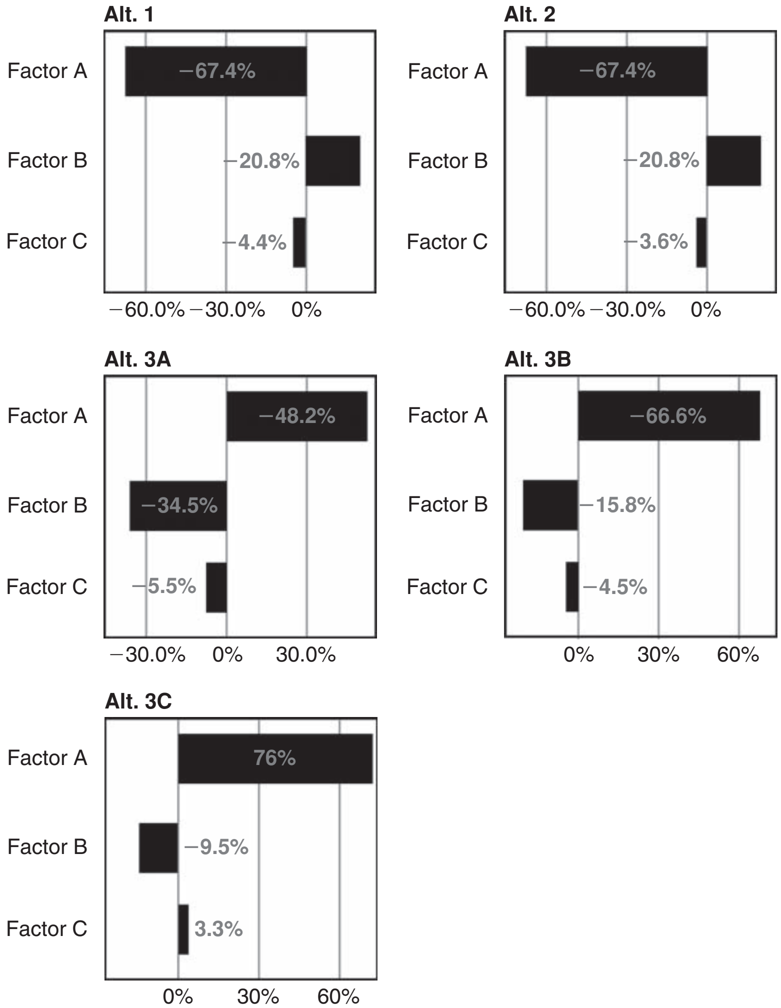


FIGURE 11.22

Simulation sensitivity results for woodland preservation performance metric.

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CHAPTER

12 DCA Application Example: Remediation

Lindsay N. Wallace

Decision Consequence Analysis (DCA) can be used to filter and inform groundwater management decisions at a site that has been impacted by pollutants. It creates a logical and consistent framework for decision making. This chapter begins by explaining a site's background and the baseline situation that is creating a need for complex land management decisions. The site is then analyzed using the DCA steps described in previous chapters:

- Identification of the baseline physical constraints
- Definition of the problem, the objectives, and the performance metrics
- Mapping of decisions and uncertainties
- Consequence analysis of the primary decision
- Decision analysis of the information decisions
- Selection of alternatives and actions that optimize achievement of the objectives

12.1 SITE BACKGROUND

The subject site (Site), located in the United States and containing 16 abandoned landfills and former solvent pits, was characterized using monitoring wells and direct push probes to determine its soil strata, groundwater elevation and direction, and contaminant concentrations over time. It was established that there are stable plumes of contamination in the groundwater, and soil contamination. The proximity of the nearby city's aquifer (City Aquifer) is also known. Site features are displayed in Figure 12.1.

The main contaminant of concern (COC) at the Site is trichloroethylene (TCE). The main plume of TCE-contaminated groundwater, having a width of approximately 100 feet, appears to be emanating from the former solvent pit area and migrating west and northwest toward the City Aquifer. It continues northward toward the Site boundary. Historical data indicates that the main plume is stable or contracting under current conditions. The contaminants are undergoing first-order decay with time and distance from the source. A smaller plume of TCE-contaminated groundwater to the west, in an area of abandoned landfills, is called

DOI: 10.1016/B978-1-85617-797-9.00012-5

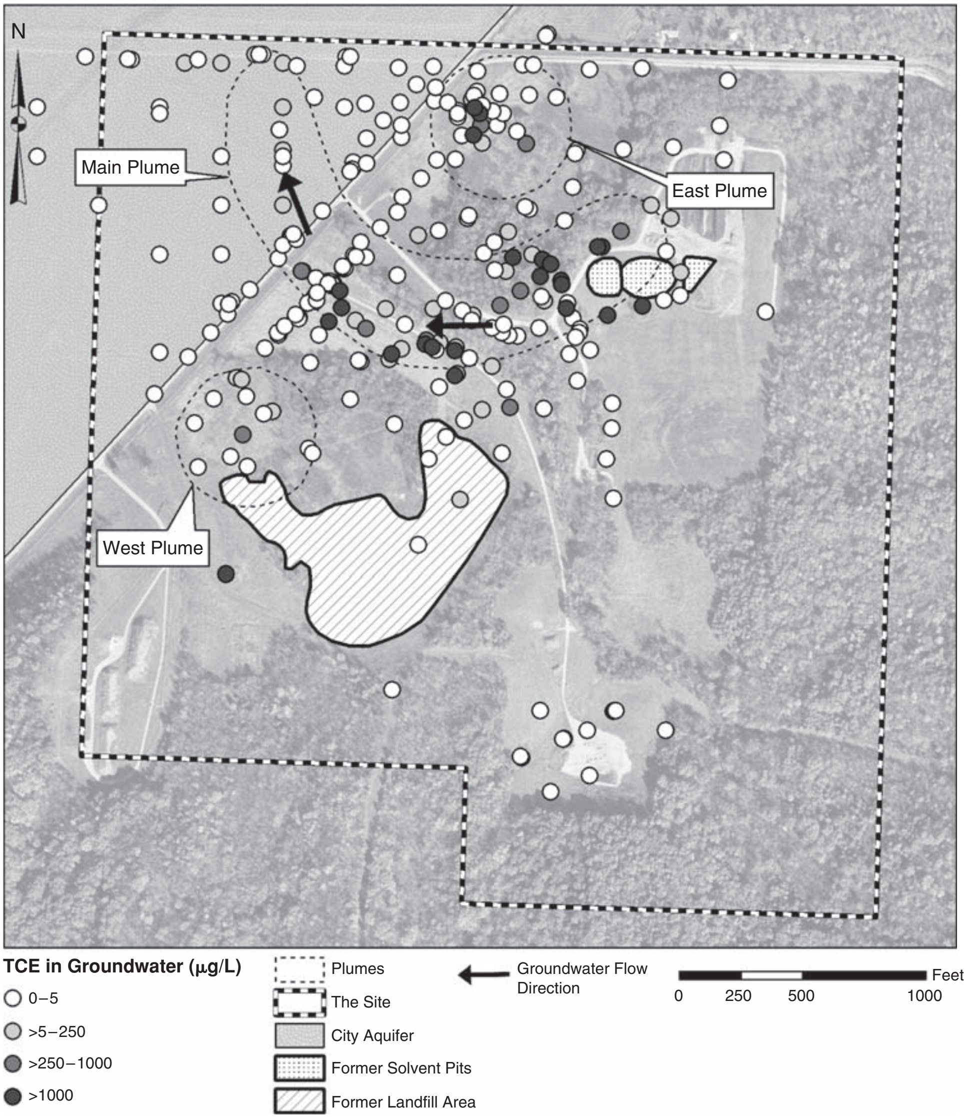


FIGURE 12.1

Baseline physical properties of the site.

the west plume. A separate TCE-contaminated groundwater area to the east is called the east plume. The east and west plumes appear to be immobile or stable.

Although no contamination above U.S. drinking water standards is currently known to be crossing the Site's property boundary, a permeable reactive wall (PRW) was constructed in 2001 to reduce further migration of TCE-contaminated groundwater into the City Aquifer. Its installation was an *interim remedial measure*—that is, a measure taken while a permanent remediation strategy is still under study. The PRW is impeding groundwater flow, raising the groundwater level upgradient of the wall so that contaminants may be discharging under and around it. This condition has been deemed unacceptable, and corrective measures to fix or improve the wall are being considered. However, a metric for quantifying the performance of the PRW relative to other groundwater management objectives must first be defined. In other words, whether or not the wall should even be part of a permanent remedy should be examined using DCA before making a decision to repair it just because it is the status quo and represents sunk costs.

12.2 IDENTIFICATION OF BASELINE PHYSICAL CONSTRAINTS

The hydrogeologic and physical constraints described in this section will establish the limits of what can and should be attempted with respect to improvement of Site groundwater. They are as follows:

Off-site property is protected. The downgradient extent of the main plume is in the vicinity of extraction well EW-2 (Figure 12.2), the only location where groundwater contaminants are present near the property boundary at concentrations above the U.S. drinking water standard. This well extracts contaminated water from the ground before it can cross the property boundary, providing hydraulic control. However, as will be discussed later, this cone of influence is also providing a steady pull on contaminated groundwater from the plume, drawing it to the well near the property boundary and thereby increasing the liability associated with this plume.

Human health is protected. Groundwater is not being consumed on the Site, and TCE levels are below the drinking water standard in groundwater off-site, across the property boundary. Figure 12.3 shows that TCE concentrations in wells near the border have decreased over time to the level of the standard or below. According to the U.S. Safe Drinking Water Act as of the date of this writing, the maximum contaminant limit (MCL) for TCE in drinking water is five parts per billion (ppb; also expressed as micrograms per liter or µg/L). While there are levels of TCE in groundwater above the MCL on the Site, no one will be drinking the water, so there is no completed *risk pathway* (see Chapter 17 for a more detailed explanation of exposure pathways).

Plumes are stable or decreasing. The former solvent pit area is the source of the main plume. The east plume has a separate immobile source; the west plume's source is the former landfill area. TCE concentrations in the east and west plumes are stable and not migrating (Figures 12.1 and 12.2). The TCE concentrations in the main plume are stable or decreasing with time and distance from the plume's source (Figure 12.3).

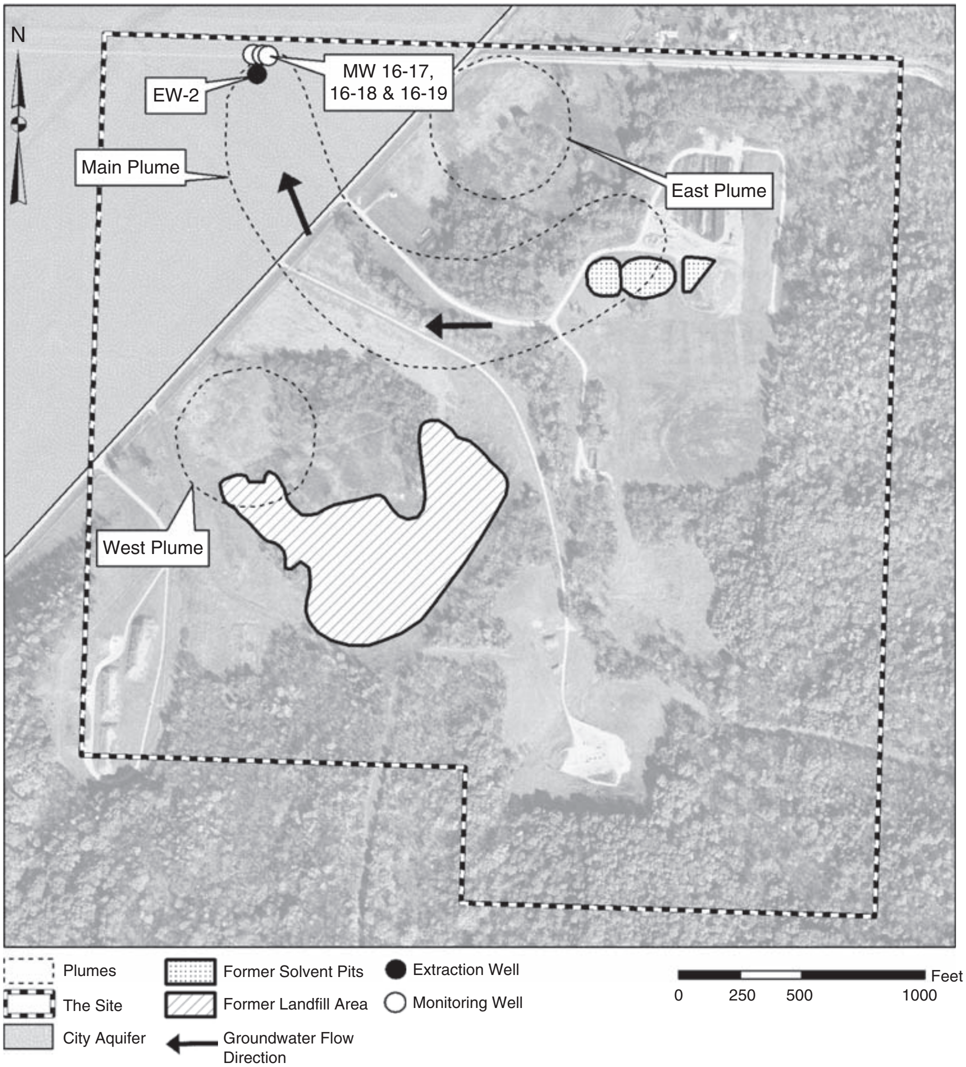


FIGURE 12.2

Downgradient wells at property boundary.

Site-specific geochemical data is known. TCE becomes diluted and will naturally degrade or attenuate in the groundwater. The site-specific *dilution and attenuation factor* (DAF) for TCE in the main plume is approximately 10 for every 500 feet and 2 for every 5 to 10 years. This means that the average concentration of TCE in groundwater decreases by a factor of 10 for every 500 feet it moves downgradient and is halved every 5 to 10 years.

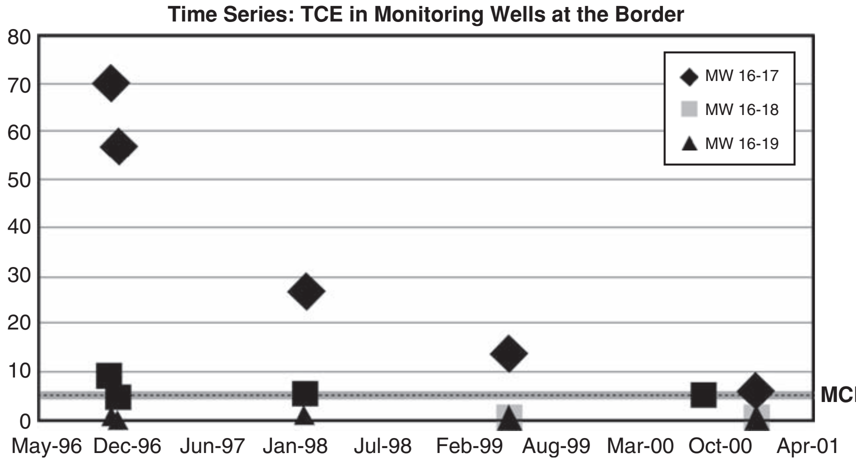


FIGURE 12.3

TCE time series at the property boundary.

Site-specific confounding factors are known. The main plume's source mass is not a candidate for removal by *pump and treat* (installation of wells to extract, treat, and reinject the water downgradient) or for significant accelerated degradation with *insitu treatment* (any of a number of methods whereby contamination is remediated in place). This is due to the characteristics of the contaminated media and the presence of the material as a non-aqueous phase liquid (NAPL) within fine-grain pore spaces, providing a continuing source of TCE under equilibrium within the stable plume.

12.3 DEFINITION OF PROBLEM, OBJECTIVES, AND PERFORMANCE METRICS

The *problem statement* must address the essence of the decision problem and accurately respond to decision *triggers* (the reasons that a problem has been identified). The *objectives* are expressions of what is to be accomplished to solve the problem. The *alternatives* are the methods by which the objectives will be met. The *performance metrics* are the means for quantifying the relative utility of each alternative for achieving each objective.

Although the trigger creating the need for a decision on the Site appears to be the failure of the PRW, we should dig deeper to find out why that is a problem in the first place. The triggers or conditions that create a need for a decision on this site are

- TCE contaminant levels above the MCL near the Site's property boundary.
- High TCE concentrations in the source area that could exacerbate plume persistence and expansion.

- Detection of TCE north of the main plume and east plume that could indicate TCE migration to an area along the Site boundary where it was not detected previously.

Remediation alternatives cannot be assessed accurately unless the relationships between the triggers and the decisions are understood. The problem statement must express these relationships in a manner ensuring that the correct problem is being addressed. It is essential that the problem statement is formulated with no unwarranted assumptions, option-limiting prejudices, concern for sunk costs, or anchoring on the status quo. (See Chapter 4 for a thorough discussion of the psychological traps that can hinder good decision making.)

12.3.1 Problem Statement

To formulate a problem statement, the *end objective* must be defined by deciding on a preliminary problem statement and asking the question "Why?" until the fundamental problem is found. Here is an example, starting with a preliminary problem statement:

- The groundwater must be protected from TCE concentrations above the MCL. Why?
- People must not drink groundwater with TCE concentrations above the MCL. Why?
- This would place people at risk.

The end objective is to protect people from risk; that is, the fundamental problem is the potential for a completed risk pathway.

The proposed problem statement for the Site is

> *Discover what performance criteria are appropriate to protect against completion of a risk pathway and what actions best achieve them.*

The first part of the problem statement addresses the end objective—the fundamental problem of protecting people from risk. The second part is recognition that there must be measurable performance criteria—the *means objectives*: How will the end objective be achieved? Remedial actions should be viewed in the context of the short- and long-term alternatives that may be applicable for achieving the appropriate performance criteria.

The *primary decision* is how to prevent completion of a risk pathway. Four alternatives are proposed for solving the fundamental problem:

Resource restoration. Restore the groundwater to potable conditions; this can be defined as achieving MCL throughout all plumes, including those in source areas.

Achievement of MCL in aquifer. Ensure that the groundwater in the City Aquifer (including the portion on the Site) has TCE levels below the MCL.

Achievement of MCL at property boundary. Ensure that groundwater at the property boundary has TCE levels below the MCL.

Protection of off-property. Prevent the off-site migration of groundwater with TCE concentrations in excess of the MCL.

The first alternative requires that the MCL for TCE be met in all groundwater, while the other three alternatives allow limited portions of the property to have groundwater in excess of the MCL as long as it does not cross into a certain area (the aquifer, the edge of the property, or off-site).

The next step is defining the *information decisions*—what needs to be learned to properly characterize the Site and select the final remedial actions? There are two major information decisions:

1. What remedial activities are appropriate for the interim solution (the PRW), given the most likely performance criteria and remedial alternatives—what is to be done about the permeable reactive wall already in place?
2. What additional characterization is necessary to assess the relative merits of permanent alternatives?

The *future decision* addresses the measurability aspect in the second part of the problem statement:

- Which alternative provides the best results for achieving the designated performance criteria?

12.3.2 Objectives

Objectives are statements of what is to be accomplished as a result of the investigation and short- and long-term remedial activities that will be implemented for the Site's groundwater. They are used as a basis for comparing the alternatives associated with the primary decision.

The EPA provides a groundwater presumptive response strategy (EPA, 1996) that defines four objectives, generally applicable for all sites with contaminated groundwater:

Objective 1. Prevent exposure to groundwater contaminated above acceptable risk levels.

Objective 2. Prevent or minimize further migration of the contaminant plume.

Objective 3. Prevent or minimize further migration of contaminants from source material to groundwater.

Objective 4. Return groundwater to its beneficial uses wherever practicable.

As recognized by the National Oil and Hazardous Substances Pollution Contingency Plan (NCP), the achievement of objectives must be measured in terms of relative benefits (e-CFR, 2009). The concept of practicability introduces the issue of cost versus benefit. Virtually anything is possible at a price—the question becomes whether the benefit outweighs or justifies the cost. The Department of Defense's Defense Environmental Restoration Program (DERP) expresses this concept in their guidance goals (ODUSD, 2001). These goals include "reducing risk to human health and the environment through implementation of effective, legally compliant, and cost-effective response actions." Therefore, a fifth objective should include consideration of the costs of alternatives:

Objective 5. Ensure cost-effective allocation of resources.

12.3.3 Performance Metrics

Performance metrics are a measure of the consequences of a particular alternative relative to each objective. The primary decision has a set of four associated alternatives, listed previously (resource restoration, MCL in aquifer, MCL at property boundary, MCL off-site). Each provides differing results relative to each of the five objectives just discussed. How well each alternative will satisfy each objective is an unknown and should be approached probabilistically. A performance metric is necessary to quantify, relative to the objectives, the benefit of each alternative. This quantification should provide both an alternative's expected consequence and a measure of the uncertainty inherent in the analysis of relative benefits.

Figure 12.4 presents the performance metrics that will be used in this analysis. The term *contaminant flux* in the figure refers to the movement of groundwater with measureable concentrations of TCE.

12.4 MAPPING OF DECISIONS AND UNCERTAINTIES

The decision process involves selecting the alternatives that best achieve the objectives. Each alternative has varying levels of uncertainty with regard to outcome. Outcomes must be assessed in terms of decision objectives. Further, each decision affects the range of options available for future decisions. The decision process consists of decide–learn–adjust–decide again. Detailing the linkages between current and future decisions, information decisions, and uncertainties reduces the potential for extensive activities that do not materially improve the quality of the final results.

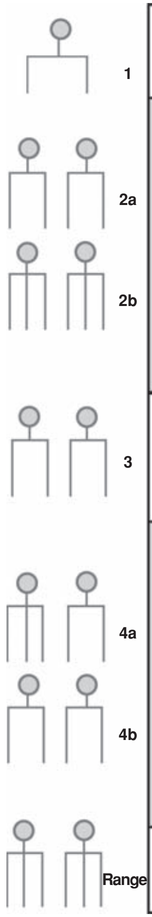
Decisions are being made regarding Site groundwater remediation to achieve the objectives discussed in Section 12.3. Uncertainty exists, however, in the consequences associated with each alternative. The uncertainty, or risk profile (risk of not achieving the desired results), can be mapped with a decision tree, which graphically represents the essence of a decision, displaying the interrelationships among choices and uncertainties. A decision tree presents, methodically and objectively, the architecture of a decision (Hammond, 1999). The interrelationships of the four primary decisions for the Site and the associated uncertainties are shown in Figure 12.5. The decisions fall into three types: primary, information, and future.

Primary decision (decision 1). What is the appropriate performance criterion (which alternative to aim for)?

	Objective	Performance Metric
1	Prevent exposure to contaminated groundwater above acceptable risk levels.	Probability of postremediation area of contaminated groundwater X Probability of use
2	Prevent or minimize futher migration of the contaminant plume (plume containment).	Probability of plume expansion
3	Prevent or minimize futher migration of contaminants from source material to groundwater (source control).	Postremediation contaminant flux over 30 years across source control boundary / Baseline contaminant flux across source control boundary
4	Return groundwater to its beneficial uses wherever practicable.	Probable restored area X Probable postremediation average concentration
5	Provide responsible stewardship of public resources.	Total life cycle cost

FIGURE 12.4

The five objectives and their performance metrics.



Decision 1—Primary Decision on Performance Criteria		Alt. 1 Resource Restoration	Alt. 2 MCL at City Aquifer Boundary	Alt. 3 MCL at Property Boundary	Alt. 4 Protect Off Property
Decision 2—Pertaining to PRW	24—Does PRW provide value for meeting the perfomance criteria or eliminating an imminent threat?	Yes	Yes	Yes	Yes
		No	No	No	No
	2b—What actions are appropriate for PRW?	Repair	Repair	Repair	Repair
		Install contingency	Install contingency	Install contingency	Install contingency
		Incorporate wall into permanent remedy	Incorporate wall into permanent remedy	Incorporate wall into permanent remedy	Incorporate wall into permanent remedy
		Decommission	Decommission	Decommission	Decommission
Decision 3—Required Characterization		Source characterization plus GW time series and sentinels	Source characterization plus GW time series and sentinels	Source characterization plus GW time series and sentinels	Source characterization plus GW time series and sentinels
		GW time series and sentinels only	GW time series and sentinels only	GW time series and sentinels only	GW time series and sentinels only
Decision 4—Restoration/Removal	Decision 4—Restoration Removal	Source excavation/ pump and treat	NA	NA	NA
		Source excavation/soil vapor extraction (SVE)	NA	NA	NA
		NA	PRW	PRW	PRW
		NA	Pump and treat	Pump and treat	Pump and treat
		NA	Phytoremediation	Phytoremediation	Phytoremediation
		NA	NA	Natural attenuation	Natural attenuation
		NA	NA	NA	Hydraulic control
	4b—Supplemental hot-spot removal	YES	YES	YES	YES
		NO	NO	NO	NO
Range of Implementation Consequences Related to Each Objective		Low	Low	Low	Low
		Nominal	Nominal	Nominal	Nominal
		High	High	High	High

FIGURE 12.5

Decision uncertainty tree.

Information decisions (decisions 2 and 3). Does the permeable reactive wall (PRW) provide value for meeting the performance criterion or for eliminating an imminent threat? What actions are appropriate for the PRW? Should required characterization include the source area?

Future decision (decision 4). What is the appropriate remedy or combination of remedies to satisfy the performance metric? Should there be supplemental source removal?

Note that, as shown on the decision uncertainty tree in Figure 12.5, the decisions are interrelated and that each combination of decision alternatives will have a unique set of potential outcomes. For example, while the need for the PRW has to be evaluated for every alternative (decision 2), as the performance criterion is modified from restoration (alternative 1) to achieving MCL at various points of compliance (alternatives 2–4), the remedy options change (decision 4). If the performance criterion is restoration, the remedy will almost certainly need to include significant contaminant removal or in situ contaminant destruction (such as soil vapor extraction or SVE).

An example of in situ contaminant destruction is *soil vapor extraction* (SVE), in which vacuums are applied to the vadose zone of the source area to extract and treat volatile contaminants as vapors. However, if the performance criterion is protection of the property boundary, the remedial options include various combinations of contaminant removal, hydraulic control, and/or in situ attenuation. One possible method is **phytoremediation**—the planting of tree species that can remediate the groundwater through natural processes of contaminant extraction, degradation or immobilization.

12.5 PRIMARY DECISION CONSEQUENCE ANALYSIS

The consequence analysis should describe how well a primary decision alternative meets the objectives. It consists of the construction of a consequence table that compares each alternative against each objective. Consequences may be described qualitatively or quantitatively utilizing the performance metrics described in Section 12.3 and shown in Figure 12.4.

12.5.1 Decision 1: What Is the Appropriate Performance Criterion?

The subsequent three decisions are governed by the primary decision: "What is the appropriate performance criterion to prevent the completion of a risk pathway?" The emphasis in this case study is on this initial decision. Subsequent decisions are addressed in the following text. As discussed in Section 12.3, there are four alternatives for the performance criteria:

- Restoring the groundwater (achieving MCL throughout)
- Achieving MCL at the City Aquifer boundary
- Achieving MCL at the Site property boundary (in which case extraction well EW-2 is not needed)
- Ensuring that contamination above the MCL does not migrate off of the property boundary (in which case EW-2 is required)

The estimated areas of compliance (within the Site boundary) for each alternative are shown on Figure 12.6.

Resource restoration is the most aggressive alternative. Its goal is the improvement of as much groundwater as possible, to the point where restrictions on future use are minimized. The alternatives of achieving MCL at the City Aquifer or at the Site property boundaries constitute an early acknowledgment that portions of the aquifer will not be restored, at least not in any reasonable time frame. Both alternatives take into account that attenuation exists with distance from the source, so satisfaction of the performance criteria can be achieved with much higher contaminant concentrations left in place. The last alternative, preventing off-site migration of groundwater with contaminant concentrations in excess of the MCL, is the least aggressive. This performance criterion is achieved with the measures currently employed. The following subsections provide consequence analyses of each alternative for each objective in Figure 12.4.

12.5.2 Objective 1: Prevent Exposure to Contaminated Groundwater

All four of the performance criteria alternatives satisfy this objective because there is no current use of the contaminated groundwater. However, it is desirable to increase confidence that its consumption will not occur in the distant future when risk reduction controls may no longer be enforced. Comparison of the alternatives as they relate to this objective measures whether the risk pathway is eliminated with or without human intervention in the distant future.

The performance metric for this objective is A × B × C, where A is the area that may be unacceptable for consumption at the time such consumption would occur, B is the probability that the area would be utilized, and C is the probability that the area would be restored to drinking water levels in 15 years. There is, for example, a reasonable probability that the City Aquifer on the site may be used. In contrast, there is a very low probability that the area in the vicinity of the sources will be used. For the purpose of this calculation, the Site is separated into distinct areas that have very different probabilities of future consumption or restoration: the source area (where the landfills and solvent pits were), the City Aquifer area, and the intermediate area (everything in between those distinct areas).

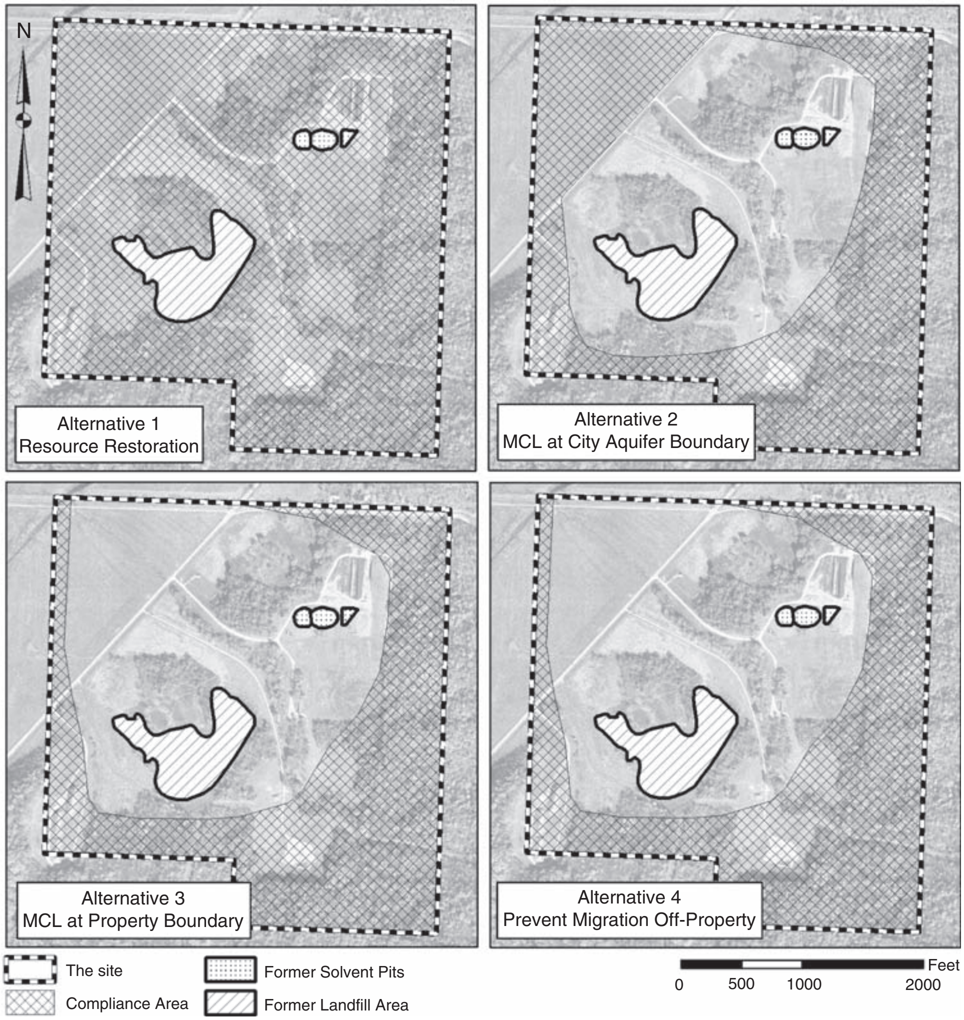


FIGURE 12.6

Four alternatives and their compliance boundaries.

The results of the consequence analysis for this objective are shown in Figure 12.7. The product of A × B × C for each alternative and area is the utility calculation. Then for each alternative, the utility calculations of the three areas are summed to obtain a relative value of the alternative's benefit. This relative benefit is converted into a dimensionless value. A value of 1 is applied to the alternative that provides the greatest utility in preventing exposure to contaminated groundwater.

		Source Area I	Intermediate Area II	City Aquifer Area III
INPUT A	Area Currently Impacted (acres)	30	45	20
INPUT B	Probability of Groundwater Consumption in the Future	0.1	0.3	0.8
INPUT C	Probability of Area Being Restored to 10^{-5} Risk within 15 years under Each Alternative			
	Alt. 1 Resource Restoration	0.1	0.5	0.5
	Alt. 2 MCL—City Aquifer Boundary	0.1	0.3	0.5
	Alt. 3 MCL—Property Boundary	0.1	0.2	0.3
	Alt. 4 MCL—Protect Off-Property	0.1	0.1	0.05

Utility Calculation ($A \times B \times C$)	Source Area I	Intermediate Area II	City Aquifer Area III	Sum of Utilities I + II + III	Relative Utility Value
Alt. 1 Resource Restoration	0.3	6.8	12.8	20.0	1.0
Alt. 2 MCL—City Aquifer Boundary	0.3	4.1	8	12.4	0.62
Alt. 3 MCL—Property Boundary	0.3	2.7	4.8	7.8	0.39
Alt. 4 Protect Off-Property	0.3	1.4	0.05	2.5	0.12

FIGURE 12.7

Calculation of relative utility values of each alternative in meeting Objective 1.

Because alternative 4 (off-site protection) is the existing condition, the dimensionless analysis provides a relative measure of the benefit of implementing more aggressive performance criteria. No alternative changes the current condition in which there is no complete pathway for ingestion of contaminated groundwater. This analysis compared the relative likelihood that a complete pathway may occur, under a given alternative, in the future. It is also important to note that the risk of exposure is never completely eliminated—no alternative will completely eliminate the contaminated groundwater, regardless of the effort expended.

12.5.3 Objective 2: Prevent or Minimize Further Migration of the Contaminant Plume (Plume Containment)

The available time series data from wells indicate a 95 percent confidence level that the plume is decreasing in concentration throughout its extent. In addition, the plume is bounded by wells with no detectable TCE concentrations except in the vicinity of extraction well EW-2. The monitoring wells in the vicinity of EW-2 (Figure 12.2) show that the plume is contracting as its boundary concentrations decrease to the MCL or below (Figure 12.3).

The data demonstrate that the forcing functions (source strength and/or hydraulic heads from liquid disposal) that created the current plume configuration are diminishing. Because the plumes are stable or collapsing, objective 2 is fully satisfied. All four of the performance criteria alternatives will produce conditions equal or superior to the existing conditions. Therefore, for this objective the relative utility value of each performance criteria alternative is equal to 1.

12.5.4 Objective 3: Prevent or Minimize Further Migration of Contaminants from Source Material to Groundwater (Source Control)

None of the four performance criteria (alternatives) will produce a remedy that is likely to eliminate flux from the source areas, which are defined as the former solvent pits and the former landfill area shown in Figures 12.1 and 12.2. The relative consequences of the four alternatives will be the likely reduction in contaminant flux. The greatest reduction would occur under the resource restoration alternative, which entails significant soil removal and/or insitu treatment. However, the data demonstrate that much of the contamination is present as a non-aqueous phase liquid (NAPL) within the soil pore space. Therefore, the source in some or all of the former solvent pits will be almost impossible to remove and thus virtually infinite unless the entire area is excavated to a depth of 30 feet or more. This is not considered as an alternative because the cost is prohibitive.

The performance metric for this objective is the relative decrease in contaminant flux under each alternative. The baseline flux is taken as the maximum concentration measured in the well closest to the source area. This well, 17-6(R), has a maximum measured concentration of 2,000 μg/L, as shown in Figure 12.8.

For each alternative, probabilities are assigned for a range of potential average starting concentrations emanating from the source. So, for alternative 4—protect off-property—we assign a probability that the starting concentration is 2,000 μg/L, as measured in a direct push technology (DPT) soil boring. Such a high concentration is almost certainly due to the presence of NAPL in the soil column; it is unlikely that this is the TCE concentration actually emanating into the groundwater from the source, since the TCE concentrations of regularly sampled monitoring wells in the source areas have never been higher than 500 μg/L. So, for alternative

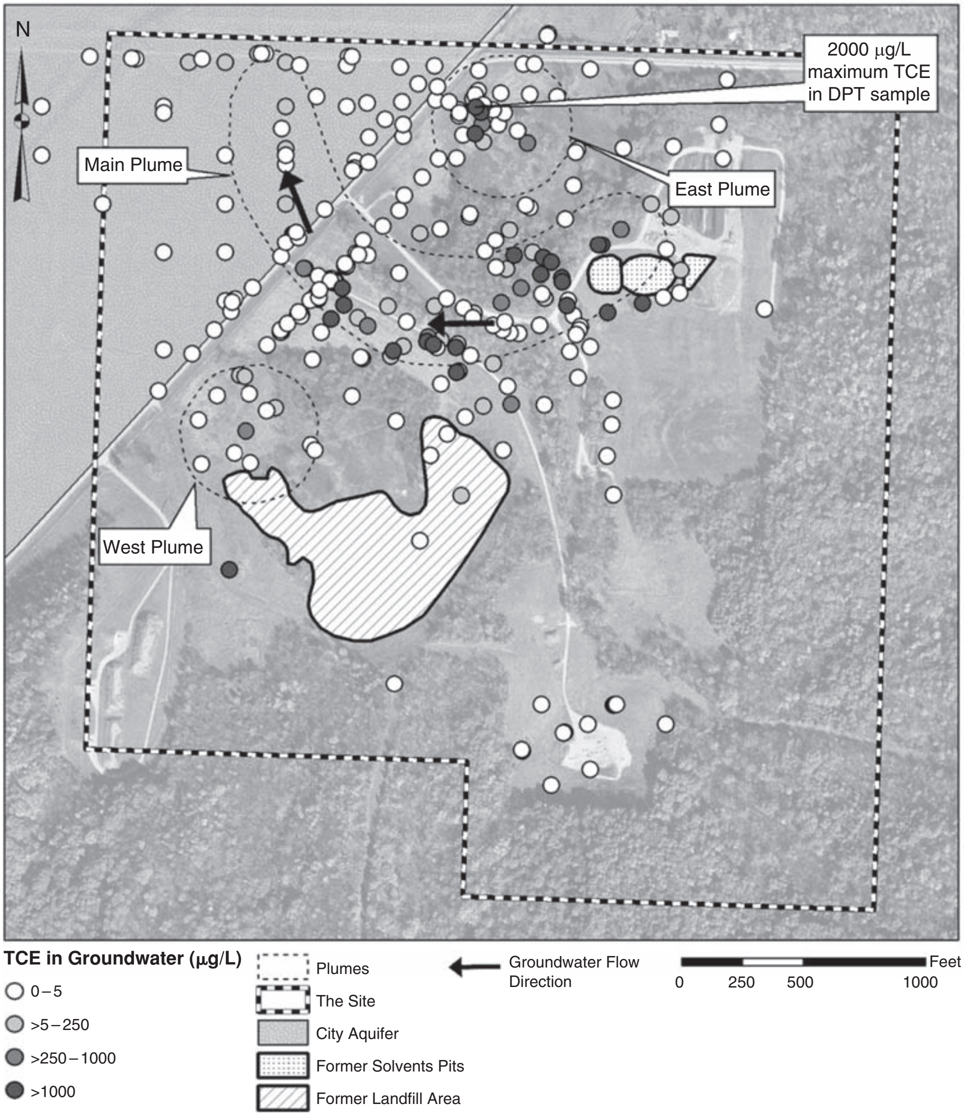


FIGURE 12.8

TCE measurement in east plume source area.

4 we also assign a probability that the starting concentration emanating from the source area may be 500 μg/L.

For each of the other alternatives, lower starting concentrations are considered—100 μg/L for alternatives 2 and 3, and both 100 and 5 μg/L for alternative 1. This is because these alternatives entail some form of source control—even source

Objective 3	
Source Control—Reduction in Flux	
Utility Calculation Results	**Relative Utility Value**
Alternative 1 Resource Restoration	**1.0**
Alternative 2 MCL at City Aquifer Boundary	**0.76**
Alternative 3 MCL at Property Boundary	**0.55**
Alternative 4 Protect Off-Property	**0.53**

FIGURE 12.9

Calculation of relative utility values of each alternative in meeting Objective 3.

removal in the case of alternative 1. Potential source values of 2,000 and 500 μg/L are still assigned some probability under those alternatives; the presence of NAPL means that there will never be 100 percent source removal without excavating the entire site to 30 feet, which is not feasible and is not being considered.

The decrease in starting concentrations is further affected by the in situ half life or attenuation that occurs naturally. As discussed in Section 12.2, the data demonstrate that the contaminant half life is between 5 and 20 years. A relative flux factor is applied to the starting concentrations. The flux factors used for this assessment are the areas under the first-order decay curves for half lives of 5, 10, and 20 years, for a duration of 30 years. Figure 12.9 presents the results of the calculation of each alternative's relative utility value for source control and flux reduction.

12.5.5 Objective 4: Return Groundwater to Beneficial Uses

Regardless of the performance criteria selected, the success of restoration of any portion of the aquifer is unknown. Also unknown are the likely average concentrations over various portions of the aquifer within the Site when the restoration is terminated. It is likely that aquifer concentrations on the Site will reach an asymptotic state at levels above the MCL.

A relative probability of reaching various stable concentrations over different portions of the plume has been assumed. For this analysis the plume has been divided into three distinct areas with differing potentials for restoration, as done earlier with objective 1.

Area 1 is approximately 30 acres in the immediate vicinity of the source areas (landfills and former solvent pits). It has a very low probability of being restored to below the TCE MCL.

Area 2 is approximately 45 acres between the source area and the City Aquifer boundary on the Site. It has a moderate possibility of being restored, but the average TCE concentration is likely to be between 1 and 4 times the MCL.

Area 3 is between the City Aquifer boundary on the Site and the Site property boundary. Approximately 20 acres of this area are currently contaminated. It has a high possibility of being restored, but average TCE concentrations may stabilize between 1 and 2 times the MCL.

The performance metric for this objective is A × P, where A is the probable area that will be restored and P is the relative value of the restoration as a function of the average stabilized concentration over the area. In this analysis, for example, a stabilized concentration of 3 times the MCL is assumed to have a relative value of 80 percent of reaching the MCL. Likewise a stabilized value of 10 times the MCL is assigned a relative value of 20 percent of the value of reaching the MCL.

The results of the consequence analysis for this objective are shown in Figure 12.10. The higher the number is, the more favorable the alternative. The values are converted into dimensionless numbers. The values in the last column indicate that alternative 4 provides 30 percent of the value of alternative 1 relative to objective 4.

Objective 4	
Return Groundwater to Beneficial Use	
Utility Calculation Results	**Relative Utility Value**
Alternative 1 Resource Restoration	**1.0**
Alternative 2 MCL at City Aquifer Boundary	**0.88**
Alternative 3 MCL at Property Boundary	**0.54**
Alternative 4 Protect Off-Property	**0.30**

FIGURE 12.10

Calculation of relative utility values of each alternative in meeting Objective 4.

12.5.6 Objective 5: Ensure Cost-Effective Allocation of Resources

The estimated costs are calculated using a probabilistic Monte Carlo analysis of the full range of potential outcomes, unit costs, and quantities for implementing the remedies that may be required to satisfy each of the performance criteria alternatives. The analysis is conducted with detailed cost data from publicly available databases, previous Site estimates, other Site estimates, and assumptions regarding the probability that different remedies may be implemented.

The full range of potential costs associated with each of the four potential performance criteria is shown in Figure 12.11. The cost analysis indicates that prompt resolution of the appropriate performance criteria is imperative. Otherwise, extensive costs will be incurred in studies and field data collection that provide no additional value. Specifically, if groundwater resource restoration (i.e., NAPL or source removal) is not implemented because of fiscal constraints, studies to determine the nature and extent of NAPL are not an appropriate expenditure of available resources.

The vertical scale (*y*-axis) in Figure 12.11 is the probability that the environmental management costs for the life of the system will be equal to or less than the value indicated on the curve. For example, the 20th percentile cost is interpreted as a cost that has an 80 percent chance of being exceeded. Conversely, the 80th percentile cost is interpreted as a cost that has only a 20 percent chance of being exceeded. The expected cost associated with a particular alternative is the 50th percentile, or median cost, among all potential outcomes. Based on experience with the uncertainty analysis technique on completed remediation projects, the dollar range between the 20th and 80th percentiles of predicted cost is an appropriate measure of liability uncertainty that should be considered in contingency planning. The uncertainty range provides a measure of the unknowns inherent in the state of knowledge, existing strategies, and regulatory status.

Figures 12.12 through 12.15 show the 20th-, 50th-, and 80th- percentile estimated costs for strategic planning; additional investigations/studies, PRW investigations, repair, and operation and maintenance (O&M); the landfill recovery trench installation and O&M; and remedial measures for each of the four alternatives. As shown, the 80th-percentile total estimated costs are significantly higher than the 20th-percentile costs. This is predominantly due to uncertainties in the remedial measures required for the achievement of each alternative. In the case of the resource restoration alternative (Figure 12.12), the need for the reactive wall and/or the recovery trench factors in the higher 80th-percentile cost. In other words, it is uncertain whether the wall and/or trench will provide significant value in achieving this goal, and either potential solution will significantly impact the cost of the resource restoration alternative.

For the alternative of achieving MCL at the City Aquifer boundary on the Site (Figure 12.13), the discrepancy between the 80th and 20th percentiles total estimated costs is predominantly due to uncertainties in whether the PRW can be repaired and whether it will be effective in preventing migration into the City Aquifer.

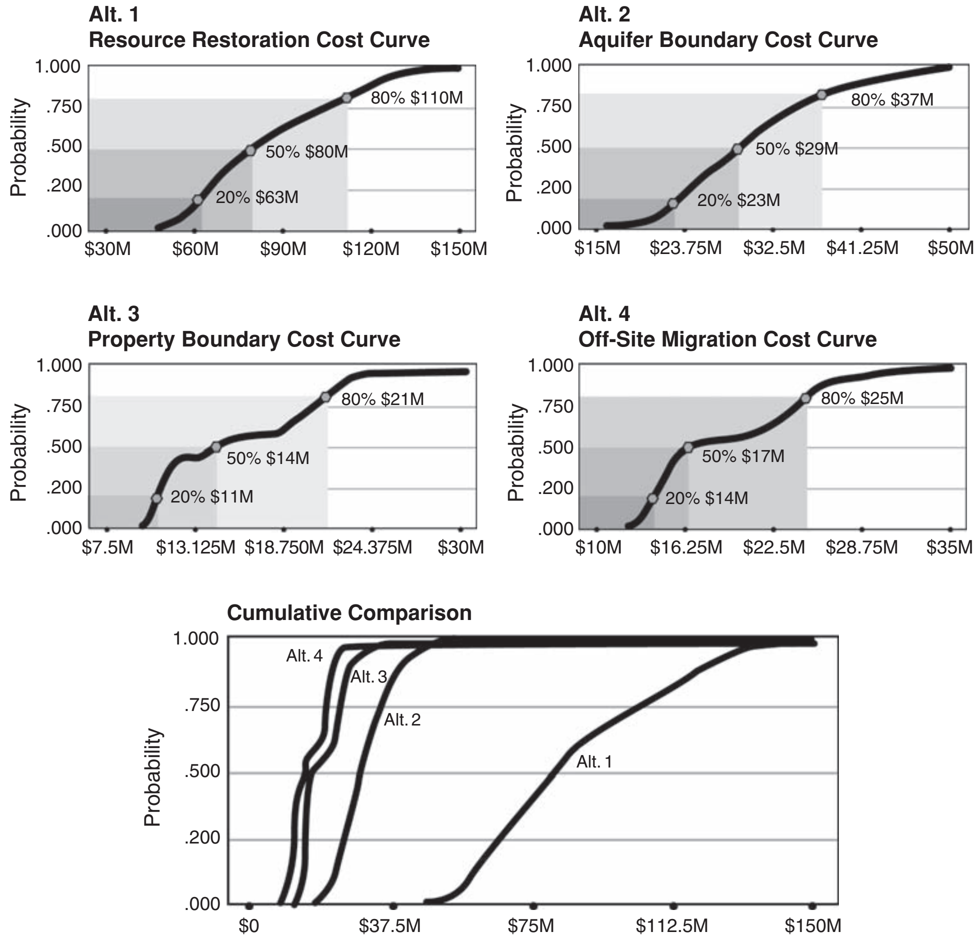


FIGURE 12.11

Probabilistic cost curves for alternatives.

For the alternatives of achieving MCL at the Site property boundary (see Figure 12.14 on page 267) and preventing off-site migration (see Figure 12.15 on page 268), the discrepancy between the 80th and 20th percentiles total estimated costs is predominantly due to uncertainties as to whether the PRW can be repaired, whether it will be effective in preventing migration of COCs (to the property boundary or off the property boundary), and whether additional measures will be required to replace the PRW. The estimated costs for preventing off-site migration are higher than the estimated costs for protecting the property boundary because it is assumed that extraction well EW-2 will be needed to prevent migration beyond the property boundary of COCs in groundwater.

Resource Restoration Estimated Costs			
Task	20th Percentile Cost	50th Percentile Cost	80th Percentile Cost
Strategic Planning/Meetings	$560,000	$570,000	$580,000
PRW Investigation, Repair and Future O&M	$1,000,000	$3,000,000	$8,000,000
Additional Investigations/Studies	$1,650,000	$1,700,000	$1,750,000
Landfill Recovery Trench Installation and Future O&M	$-	$4,600,000	$6,000,000
Remedial Measures	$59,700,000	$70,500,000	$94,000,000
Total Estimated Cost	$62,910,000	$80,370,000	$110,330,000

FIGURE 12.12

Resource restoration, estimated costs.

12.5.7 Summary

A summary consequence table of the four alternative performance criteria is shown in Figure 12.16 (see page 268). The dimensionless values provide a method of comparing the relative utility that each alternative provides in achieving the objectives as defined. Figures 12.17 and 12.18 (see pages 269 and 270) demonstrate the relative benefits associated with each alternative.

Alternative 1 (resource restoration) is recommended for elimination because the added benefits are not commensurate with the difference in cost. In effect, the additional $50 million potentially associated with this alternative provides little more than a possibility that an additional 20 to 30 acres may be returned to drinking water standards. Alternative 4 (prevent off-site migration) is recommended for elimination because its consequences are less attractive for each of the five objectives than those of any of the other alternatives, even one of lower cost.

Of the remaining two performance criteria alternatives, alternative 3 (achievement of MCL at the property boundary) is recommended as providing the most responsible allocation of resources. Alternative 2 (achievement of MCL at the City Aquifer on Site) is twice the cost, with the only added benefit being the potential restoration to drinking water standards of an additional 20 acres of the City Aquifer.

MCL at City Aquifer Boundary			
Task	20th Percentile Cost	50th Percentile Cost	80th Percentile Cost
Strategic Planning/Meetings	$560,000	$570,000	$580,000
PRW Investigation, Repair and Future O&M	$1,000,000	$3,000,000	$8,300,000
Additional Investigations/Studies	$3,300,000	$3,650,000	$4,000,000
Landfill Recovery Trench Installation and Future O&M	$5,200,000	$5,800,000	$6,400,000
Remedial Measures	$12,500,000	$15,500,000	$20,800,000
Total Estimated Cost	$22,560,000	$28,570,000	$40,080,000

FIGURE 12.13

Achieving MCL at the city aquifer boundary, estimated costs.

These 20 acres are not at high risk for future groundwater use because they are on the Site property, and there is no current or reasonably anticipated future use of groundwater. Additionally, the City Aquifer for all of the landfill area immediately to the west will be restricted from use indefinitely because of contamination. An expenditure of $15 million for possible restoration of 20 acres of an aquifer on Site property that will remain restricted for other reasons is a low-value return on resource expenditure. The remaining decisions are assessed in terms of alternative 3 (achieving MCL at the property boundary) as the appropriate performance criteria.

12.6 INFORMATION DECISIONS ANALYSIS

The decision trees in this section analyze the relationships between the information decisions and the range of realistic alternatives for the chosen remedy. There are two major information decisions: decisions 2 and 3 (decision 1 was the primary decision, discussed in Section 12.5).

Decision 2. What is the appropriate modification of the PRW?

Decision 3. What is the appropriate level of additional groundwater and source material characterization?

MCL at Property Boundary Estimated Costs			
Task	20th Percentile Cost	50th Percentile Cost	80th Percentile Cost
Strategic Planning/Meetings	$560,000	$570,000	$580,000
PRW Investigation, Repair and Future O&M	$1,200,000	$3,050,000	$9,300,000
Additional Investigations/Studies	$3,300,000	$3,650,000	$4,000,000
Landfill Recovery Trench Installation and Future O&M	$5,200,000	$5,800,000	$6,400,000
Remedial Measures	$300,000	$350,000	$400,000
Total Estimated Cost	$10,560,000	$13,420,000	$20,680,000

FIGURE 12.14

Achieving MCL at the Site property boundary, estimated costs.

The information decisions are included in this case study to improve the focus and value of studies and activities considered for modifying the PRW and for providing additional characterization of the contaminant distribution. This procedure is a variation of the data quality objectives (DQO) process. The following two subsections provide an analysis of the uncertainties, alternatives, and intermediate decisions associated with the information decisions.

12.6.1 Decision 2: What Action Must Be Taken Regarding the Permeable Reactive Wall?

Decision 2 must address several levels of uncertainty. Its trigger has two elements:

- The PRW was not installed in accordance with the design specifications approved by the EPA.
- Following installation, the groundwater levels upgradient of the PRW rose, causing a groundwater mound.

Protect Off-Property Estimated Costs			
Task	20th Percentile Cost	50th Percentile Cost	80th Percentile Cost
Strategic Planning/Meetings	$560,000	$570,000	$580,000
PRW Investigation, Repair and Future O&M	$1,000,000	$3,030,000	$9,300,000
Additional Investigations/Studies	$3,300,000	$3,650,000	$4,000,000
Landfill Recovery Trench Installation and Future O&M	$5,200,000	$5,800,000	$6,400,000
Remedial Measures	$3,300,000	$4,150,000	$5,200,000
Total Estimated Cost	$13,360,000	$17,200,000	$25,480,000

FIGURE 12.15

Preventing off-site migration, estimated costs.

Consequence Table				
Relative utility of each alternative with respect to the objectives	Alt. 1 MCL at City Aquifer Boundary	Alt. 2 MCL at City Aquifer Boundary	Alt. 3 MCL at Property Boundary	Alt. 4 Protect Off-Property
Obj. 1 Prevent Exposure	1.0	0.62	0.39	0.12
Obj. 2 Plume Control	Equal	Equal	Equal	Equal
Obj. 3 Source Control	1.0	0.76	0.55	0.53
Obj. 4 Restoration	1.0	0.88	0.54	0.3
Obj. 5 Cost (50 Percentile, in Millions)	$80.3	$29.2	$14.2	$16.6

FIGURE 12.16

Relative utility of each alternative with respect to the five objectives.

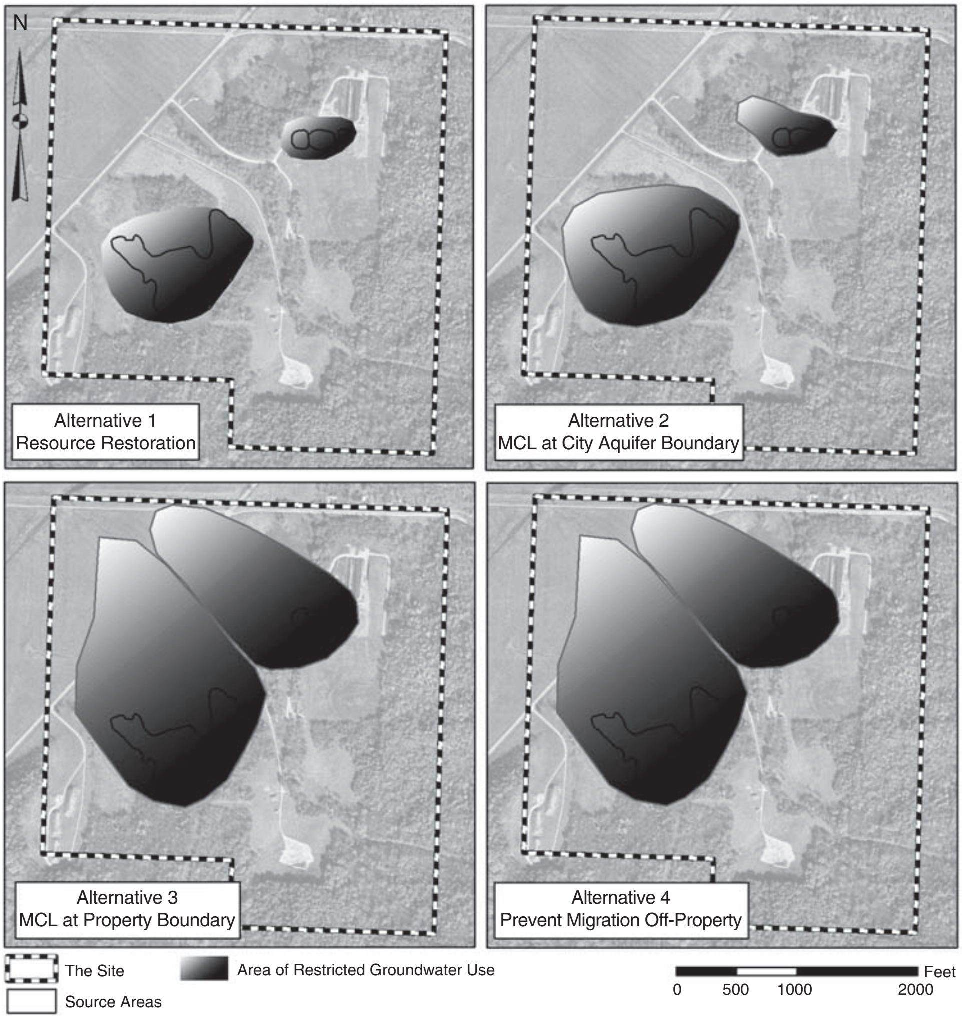


FIGURE 12.17

Anticipated areas of remaining contaminated groundwater (Objective 1) under each proposed alternative.

Because of these two conditions, regulators concluded that the PRW was not working. However, no definition was established for how "working" was to be measured. The EPA defined the PRW as an interim remedial action and found that the wall, or a similar approach to limiting groundwater contaminant flux into the City Aquifer, was necessary to protect human health and the environment.

The decision to construct a PRW was based on the assumption that there was a threat to human health and the environment, which was not an accurate

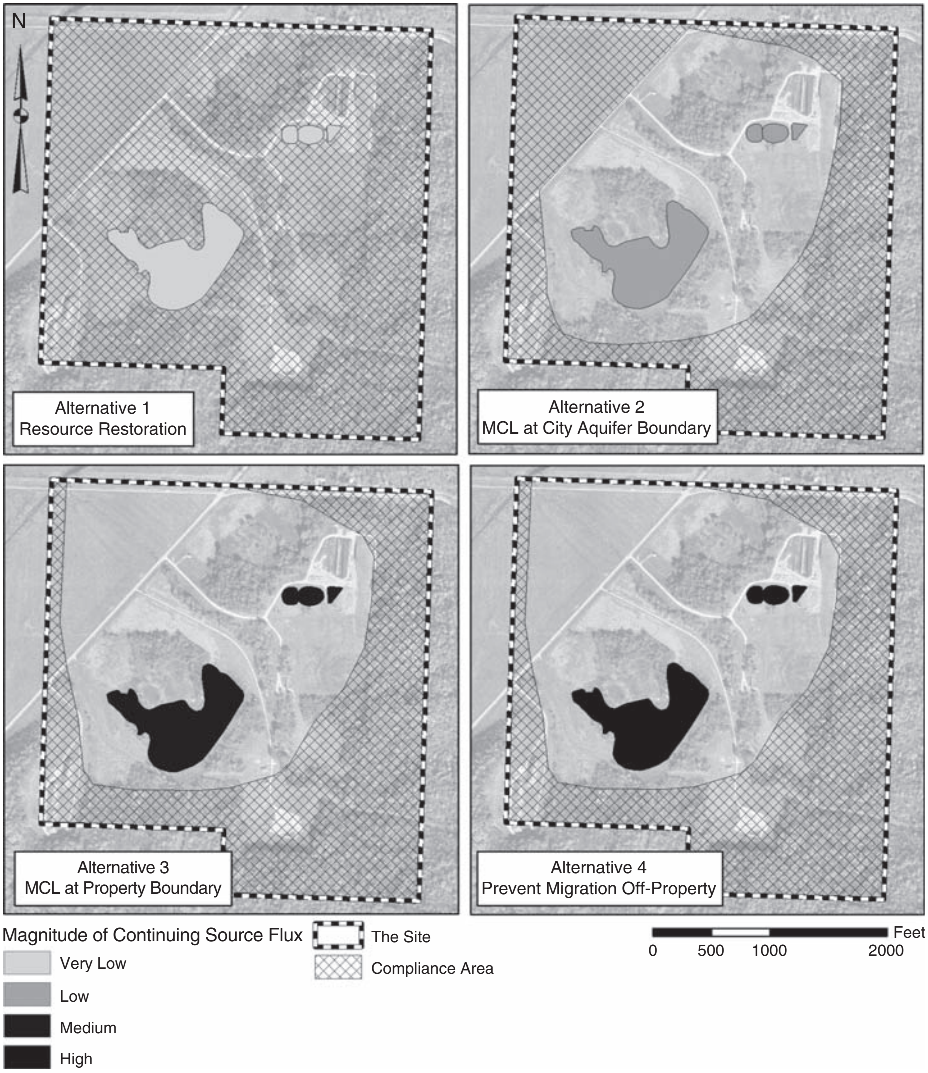


FIGURE 12.18

Anticipated relative magnitude of continuing source flux (Objective 3) and anticipated areas of groundwater returned to beneficial use (Objective 4) under each proposed alternative.

representation of the current reality; the assumption was not supported by the data. By the time the PRW was installed, contaminant concentrations at the property boundary had declined to levels compliant with the drinking water MCLs. That decline was likely due to the impact of pumping groundwater from extraction well EW-2. Nevertheless, the outcome sought with installation of the PRW had been achieved.

There is no quantitative performance metric against which the PRW can be judged, since the condition leading to its installation was eliminated before the installation was complete. The objective of the interim remedial action has been satisfied by means other than the PRW, so the need for the interim remedial action no longer exists.

The installation of the PRW was not the objective of remediation but rather was a means to an end. The "end" was eliminating an imminent risk pathway. Repairing the PRW is not a goal in and of itself. It should be considered in the context of eliminating imminent threats to the environment or potentially achieving the long-term performance criteria of meeting/maintaining groundwater concentrations at the property boundary in compliance with the MCL without operating extraction-well EW-2.

The framework for linking the uncertainties is shown in Figures 12.19(a) and (b). Nodes 1, 2, and 3 address the need for the PRW as an interim remedial action. Nodes 4 through 7 deal with the potential actions for the wall in the event it is essential for guarding against an imminent threat to human health or the environment. Node 8 is included to demonstrate the connection between the PRW decisions and the long-term decisions regarding a permanent remedy. The decision analysis for node 8 is provided in Section 12.7, which deals with the future decision.

In the decision tree, the first three uncertainty nodes (1, 2, and 3) address the need for the PRW. This portion of the tree is shown in greater detail in Figures 12.20(a) and 12.20(b). The available evidence indicates that the existing dilution and attenuation factor (DAF) of the TCE plume is sufficient to achieve concentrations at or below the MCL at the property boundary. This conclusion must be tentative given the paucity of data, and it is recommended that the conclusion be tested with additional monitoring well data along the plume centerline. To assess the DAF, temporal information is essential.

Given that there is almost always interest in resolving short- and long-term management decisions promptly, the time span for temporal data is likely to be less than ideal. Therefore, data should be collected over a minimum of six months, from at least three sampling events—one at the time the new wells are installed along the plume centerline, followed by one every three months (quarterly). Furthermore, it is unknown whether additional data is available but is not in the current database. Creating a complete database with all analytical data and sampling information is a priority, since the lack of data hinders decision making. Double-checking the completeness and accuracy of the database used for decision making is more cost-effective than further rounds of sampling, and can often produce the same result (i.e., giving a more robust and accurate picture of the facts on the ground, present and past).

The results of the sampling, including groundwater level (potentiometric) data, should be sufficient to calibrate a model of groundwater flow (without attempting the more involved task of calibrating a fate and transport model). Such a hydrodynamic model will provide a way to estimate the DAF based purely on dilution from

Node	Decision	If the answer is...	Go to Node
1	Reduction of contaminant concentrations at the City Aquifer boundary needed to meet performance criteria.	Yes	3
		No	2
2	Confidence level greater than or equal to 95% that upgradient concentrations stable or decreasing.	Yes	8a
		No	3
3	Permeable reactive wall (PRW) necessary to achieve required dilution and attenuation factor (DAF).	Yes	4
		No	8a
4	What is the most value-added modification to the PRW?	**4a** Restore design hydraulics	5a
		4b Convert PRW to funnel & gate	6
		4c Convert PRW to barrier with recovery	7a
5a	What is fouling the mechanism?	Residual Slurry	
		Biofouling	5b
		Mineral precipitation	
		Clay particulates	
5b	Repair for biofouling.	Internal flush with acid	
		Upgradient flush with acid	
6	Should PRW be extended for funnel and gate?	Yes	
		No	
7a	Should wall be extended for barrier with recovery?	No	7b
		Wiring walls	
7b	Choose upgradient groundwater management.	Pump and treat	
		Horizontal drain into treatment	
		Horizontal drain with phytroremediation	
8a	Choose permanent remedy to achieve dependable DAF.	Modified PRW	8b
		Phytroremediation	
		In situ treatment of source	
		Pump and treat	
8b	Is supplemental source removal necessary?	Yes	
		No	

FIGURE 12.19(a)

Framework for linking the decision 2 uncertainties.

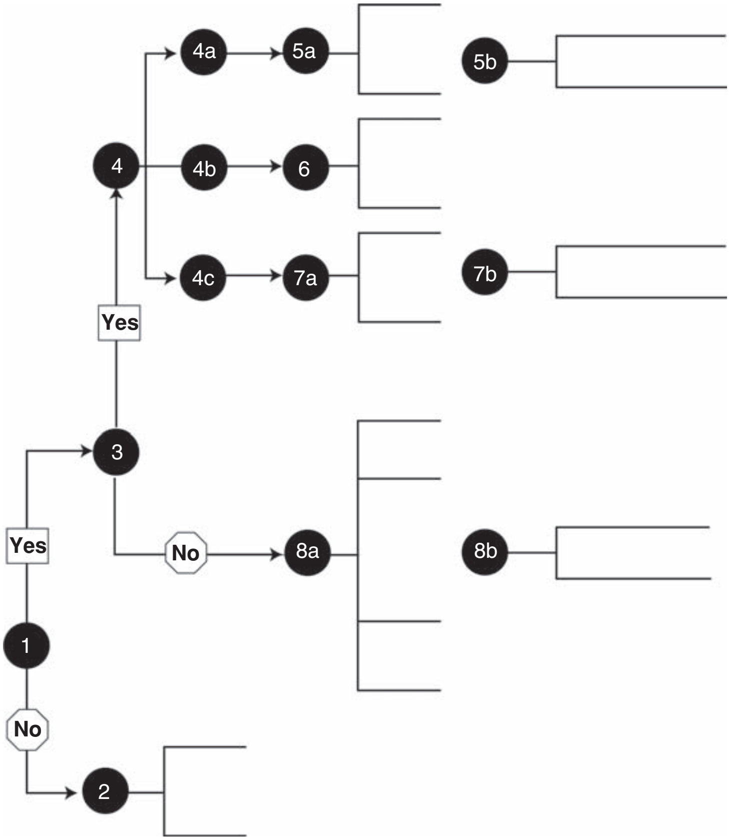


FIGURE 12.19(b)

Graphic representation of decision tree for decision 2.

rainwater infiltration. This effort will be sufficient to estimate the minimum DAF likely without pumping and the maximum concentration of TCE that can be tolerated at the City Aquifer boundary without violating the property boundary MCL performance criteria. Coupled with several additional months of pumping data, this information will allow the immediate need for the PRW to be determined.

If the PRW is not essential for short-term protection against imminent endangerment, investigations of its function are needed only to determine its relative value in ultimately reducing long-term pump and treat costs. If the PRW is determined to be necessary for protection against imminent endangerment, the questions presented in nodes 4 through 7 of the decision tree will need to be answered. Node 4a, presented in greater detail in Figures 12.21(a) and 12.21(b), addresses the probable mechanism causing the PRW to impede the flow of groundwater. The PRW's low permeability is likely the result of guar gum,

1	The reduction of contaminant concentrations at the City Aquifer boundary needed to meet performance criteria.
2	Confidence level greater than or equal to 95% that upgradient concentrations stable or decreasing.
3	Is PRW necessary to achieve required DAF?
4	What is the most value-added modification to the PRW?
8a	Determine appropriate permanent measures to reduce concentration and/or increase DAF to achieve MCL at property boundary without pumping.
A	Decision 1: Alternative 3—Performance criteria is MCL at property boundary.
B	Is existing DAF sufficient to meet MCL at property?
C	Are near-team modifications of pumping in City Aquifer feasible to achieve DAF?
D	Modify pumping accordingly.
E	Determine near-term modifications of PRW to protect boundary.
F	Install additional wells along centerline in City Aquifer (3 sets at 200 ft interval) Collect quarterly data in centerline wells (2 quarters).
G	Using hydrodynamic model, estimate DAF from City Aquifer boundary to property boundary with and without pricing.
H	Is concentration a City Aquifer boundary coupled with nonpumping DAF sufficient to meet MCL at property boundary?
I	Pilot tests of nonpumping conditions.
J	Nonpumping DAF provided sufficient to satisfy property boundary MCL.
K	Calculate confidence interval that plume concentrations upgradient of City Aquifer are stable or decreasing between sampling events using double T-test.
L	Are conditions throughout the plume improving?
M	Implement long-term monitoring.

FIGURE 12.20(a)

The need for the PRW for decision 2, nodes 1 to 3.

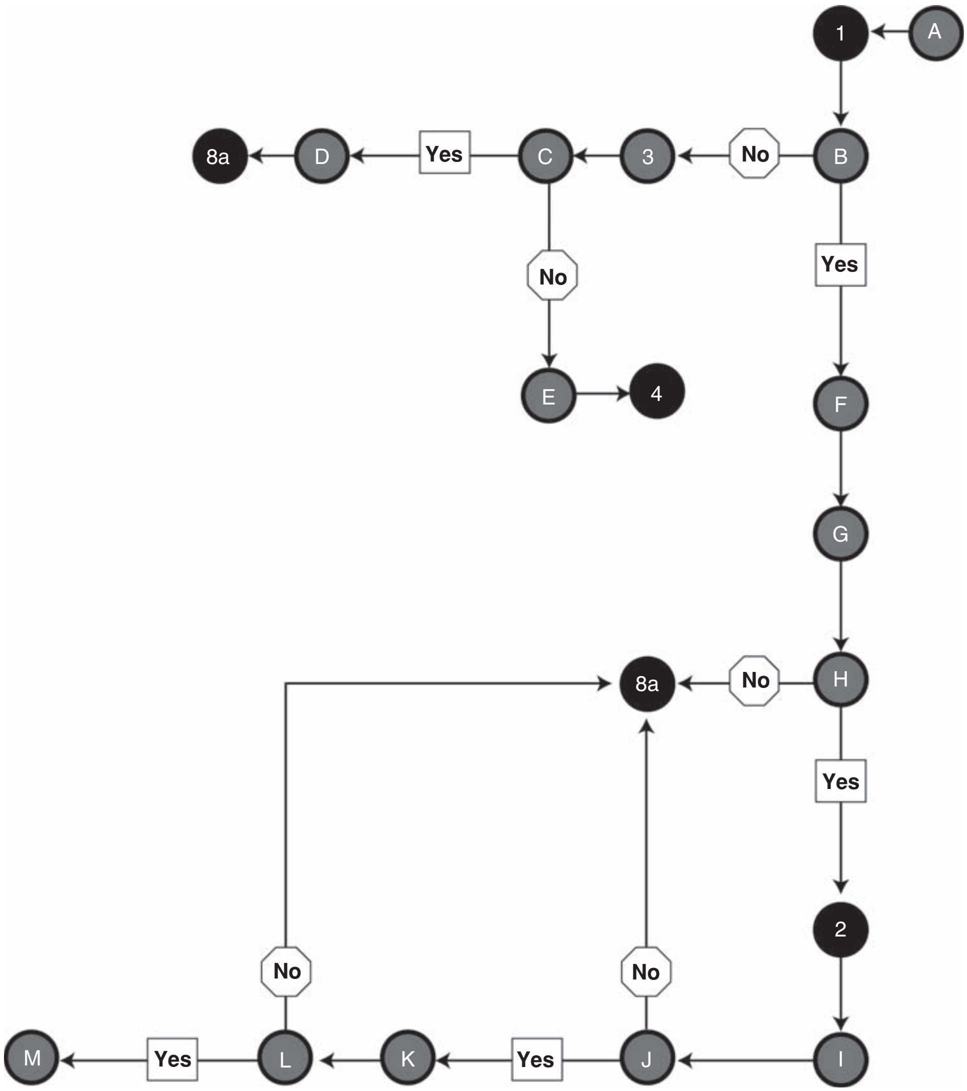


FIGURE 12.20(b)

Graphic representation of decision tree for decision 2, nodes 1 to 3.

fine-grained sediments, biological fouling, or precipitate. It appears that only the guar gum or fine-grained sediment problems can potentially be treated. Whatever conditions are present, the ability to achieve the desired permeability is unknown.

Equally important, it is unknown how effective the PRW may be in reducing TCE concentrations. The design documents did not establish what reduction of

TCE concentration would constitute the PRW "working." The Site has an interim Record of Decision (ROD—a public document explaining which cleanup alternatives will be used to clean up a Superfund site) that could be interpreted as envisioning that the PRW would remove all TCE present in the groundwater flowing through it. Even if the PRW accomplished this impressive feat, TCE concentrations below the wall would remain well above MCL levels indefinitely because of existing downgradient contamination. No mechanism was been defined for distinguishing between the existing TCE in the City Aquifer and the contribution of TCE discharging through the PRW.

The conditions regarding PRW performance are described in Figure 12.21 as "hydraulic heads equalized on either side of the wall" and "wall creates concentrations downgradient sufficient to satisfy the performance criteria" (MCL at the property boundary). If the PRW is unable to achieve these conditions, and short-term actions are needed to protect against imminent endangerment, supplemental activity will be required, which of necessity will be some type of groundwater removal either through drains or through vertical wells (nodes 4b and 4c in Figure 12.19).

If it is determined that the PRW is not necessary to achieve short-term protection against imminent endangerment, its operation should be assessed against the other potential long-term remedial actions. Decommissioning may be required if it is concluded that the PRW in its current condition is creating an unacceptable migration of the plume (around or under it).

12.6.2 Decision 3: Additional Groundwater and Source Characterizations

Data from the groundwater monitoring well and sampling network demonstrate the following:

- A 90 percent confidence that the overall groundwater plume is stable or decreasing in concentration.
- The Site boundary is protected against exceeding the TCE MCL under current conditions.
- Potentially mobile source material is in the vicinity of the solvent pits, migrating west and north through the valley that is centered in the Site.
- High TCE concentrations in the east plume represent NAPL associated with a localized release. Data demonstrate that this material is not mobile and does not threaten compliance with the MCL at the property boundary.

These conclusions, especially the relationship between contaminants and the property boundary, should be tested with additional data, which should represent aquifer conditions and provide dependable time series information. Time series information is essential to estimate DAFs and temporal plume decay rates.

4	What is the most value-added modification to the PRW?
8a	Determine appropriate permanent measures to reduce concentration and/or increase DAF to achieve MCL at property boundary without pumping.
A	PRW critical for satisfying the performance criteria in the near term.
B	Install additional water quality–monitoring wells along face of wall upgradient and downgradient. Monitor monthly.
C	Conduct and evaluate hydrogeologic tests on and adjacent to PRW. Advance cores to determine if guar, fine-grained sediment, or smearing is present and potentially causing low permeability.
D	Do cores indicate permeability loss to guar?
E	Treat wall with enzymes.
F	Do hydraulic heads equalize on either side of the wall?
G	Does the wall create concentrations downgradient sufficient to satisfy the performance standard?
H	Install hydraulic relief system (pumps or horizontal drain) and discharge to treatment plant.
I	Do cores and hydrogeologic tests indicate that fine-grained sediments or smearing may be causing low permeability?
J	Conduct pumping of PRW to attempt to improve the permeability by removing fine-grained sediments or smear-zone materials.
K	Determine hydrogeologic and COC transport ramification of PRW in current and likely future state.
L	Will PRW current and likely future state be adverse to achieving performance criteria?
M	Decommission the PRW.

FIGURE 12.21(a)

The probable mechanism causing the PRW for decision 2, node 4a.

Figure 12.22 presents the logic for further sampling and the decisions that would be developed from the additional data. The critical message is that additional source characterization is not appropriate until it is determined that source removal materially benefits achievement of the appropriate performance criteria. If the boundary is protected and the plume is stable or decreasing, source removal provides no such benefit. Removal would be beneficial only if it allowed more timely termination of the pumping currently needed to protect a portion of the property boundary.

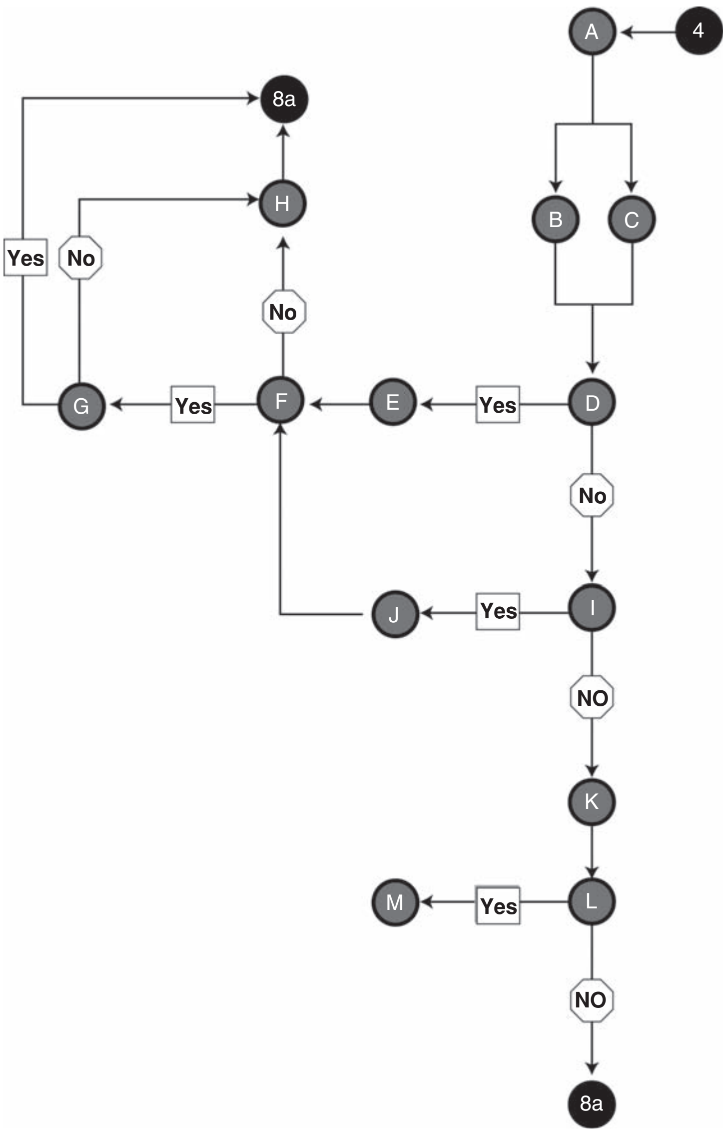
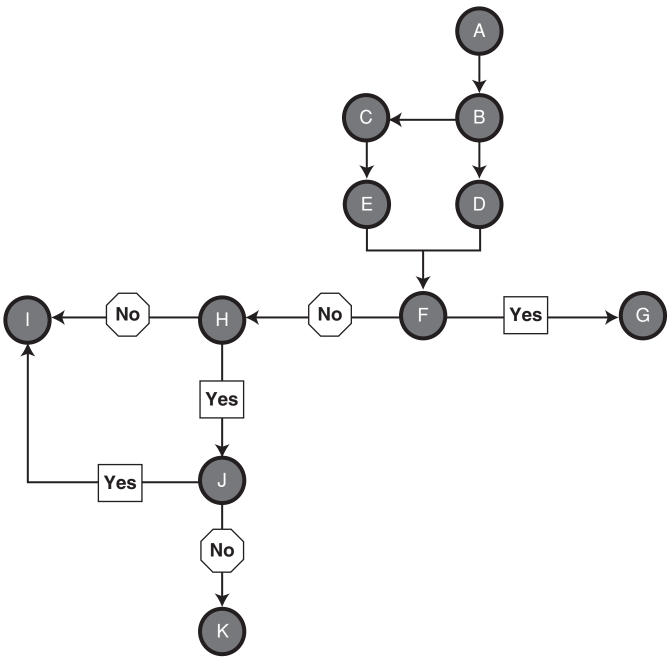


FIGURE 12.21(b)

Graphic representation of decision tree for decision 2, node 4a.

A	Decision 1: Alternative 3—Performance criteria is MCL at property boundary.
8a	Install sentinel (200 ft from boundary) and boundary wells (at property boundary) along northern boundary (2 sets at 500 ft intervals) / Collect monthly data for six months.
B	Estimate probable concentration (present and future) at the City Aquifer boundary without the PRW (based on time series data upgradient and downgradient of the PRW).
C	Collect minimum of two rounds of synoptic data, two months apart at all wells on site.
D	If there is an MCL exceedance at a sentinel well, estimate DAF from sentinel well to property boundary with and without pumping or other intervention.
E	Estimate plume-wide decay rate.
F	Is COC concentration at sentinel wells under nonintervention sufficient to meet MCL at property boundary with over 90% confidence level?
G	Additional characterization is necessary.
H	Is source removal or management likely to achieve performance criteria without intervention?
I	Additional characterization is not necessary.
J	Are source areas bounded?
K	Additional characterization of source areas may be useful.

(a)



(b)

FIGURE 12.22

Decision tree for decision 3.

12.7 SELECTION OF ALTERNATIVES AND ACTIONS

The final step in the DCA is selection of a recommended course of action that optimizes the utility of expenditures for managing the Site groundwater. The course of action selected will be a starting point for developing consensus among the various stakeholders. DCA is a tool for testing the sensitivity of the conclusions against varying stakeholder opinions.

12.7.1 Decision 4: What Remedies Are Appropriate to Satisfy the Performance Criteria?

A decision tree for assessing the best combination of permanent remedies is provided in Figures 12.23(a) and 12.23(b). The decision logic follows the mandate that the more passive the remedy is, the more sustainable it will be. Passive systems, such as phytoremediation, if effective in providing the DAFs and concentration reductions needed to achieve the MCL at the property boundary, are preferable. The goal is implementation of self-sustaining systems that require minimal human intervention.

The prioritization of potential remediation systems is as follows:

- Phytoremediation (trees in the valley upgradient of the PRW)
- Insitu treatment in the vicinity of the PRW, either with the PRW or with additives such as HRC (hydrogen release compound)
- "Hot spot" source removal
- Localized pump and treat

Note that combinations of these systems may be implemented based on the lowest-cost option that provides dependable maintenance of MCLs at the property boundary.

12.8 CONCLUSION AND RECOMMENDATIONS

Upon completion of the DCA for this Site, a complete database for target COCs should be created that includes all pertinent current and historical analytical data and sampling information. This database should be designed for easy use by stakeholders. Furthermore, before any additional studies are conducted, it should be established with all stakeholders that the performance criterion against which all activities will be measured is attainment of MCLs at the property boundary.

For additional studies to obtain groundwater analytical data, monitoring wells should be installed and monitored along the centerline of the plume, upgradient and downgradient of the PRW, and sentinel and boundary wells should be installed and monitored along the north boundary of the Site, east of the east plume. Synoptic monitoring of all Site wells (including the new ones) should be conducted for two quarters (once every three months for six months). Efforts to

A	Decision 1: Alternative 3—Performance criteria is MCL at property boundary.
8a	Decision 4: Choose permanent remedies to achieve dependable dilution and attenuation factor.
B	Estimate probable concentration (present and future) at the City Aquifer boundary without the PRW (based on time series data upgradient and downgradient of the PRW).
C	Run hydronamic model to predict travel time and DAF based on dilution only from the City Aquifer to the property boundary (without pumping at EW-2).
D	Find (1) maximum DAF needed with no change in City Aquifer boundary concentration and (2) minimum concentration needed at City Aquifer boundary if no change in existing DAF.
E	Can passive controls (phytopumping) in valley upgradient of PRW increase DAF through decreasing contaminant and/or groundwater flux?
F	Choose phytopumping/phytoremediation remedy.
G	Can in situ treatment (e.g., hydrogen release compound (HRC) or equivalent) in vicinity of PRW achieve performance criteria without supplemental DAF improvements?
H	Is there a cost-effective in situ treatment?
I	Implement an in situ additive in the vicinity of PRW.
J	Implement PRW maintenance.
K	Is there a cost-effective in situ treatment?
L	Implement phytopumping with in situ treatment such as HRC downgradient of PRW.
M	Implement phytopumping with PRW.
N	With source removal decrease COC concentration is sufficient for DAF to achieve performance criteria?
O	Establish most cost-effective combination of pump and treat/in situ treatment and phytoremediation.
P	Does the improvement decrease the time for passive conditions to be effective by greater than 15 years?
Q	Include source removal in economic assessment of site management options.
R	Continue pump and treat untill passive conditions are sufficient options.

FIGURE 12.23(a)

Decision tree for assessing the best combination of permanent remedies for decision 4.

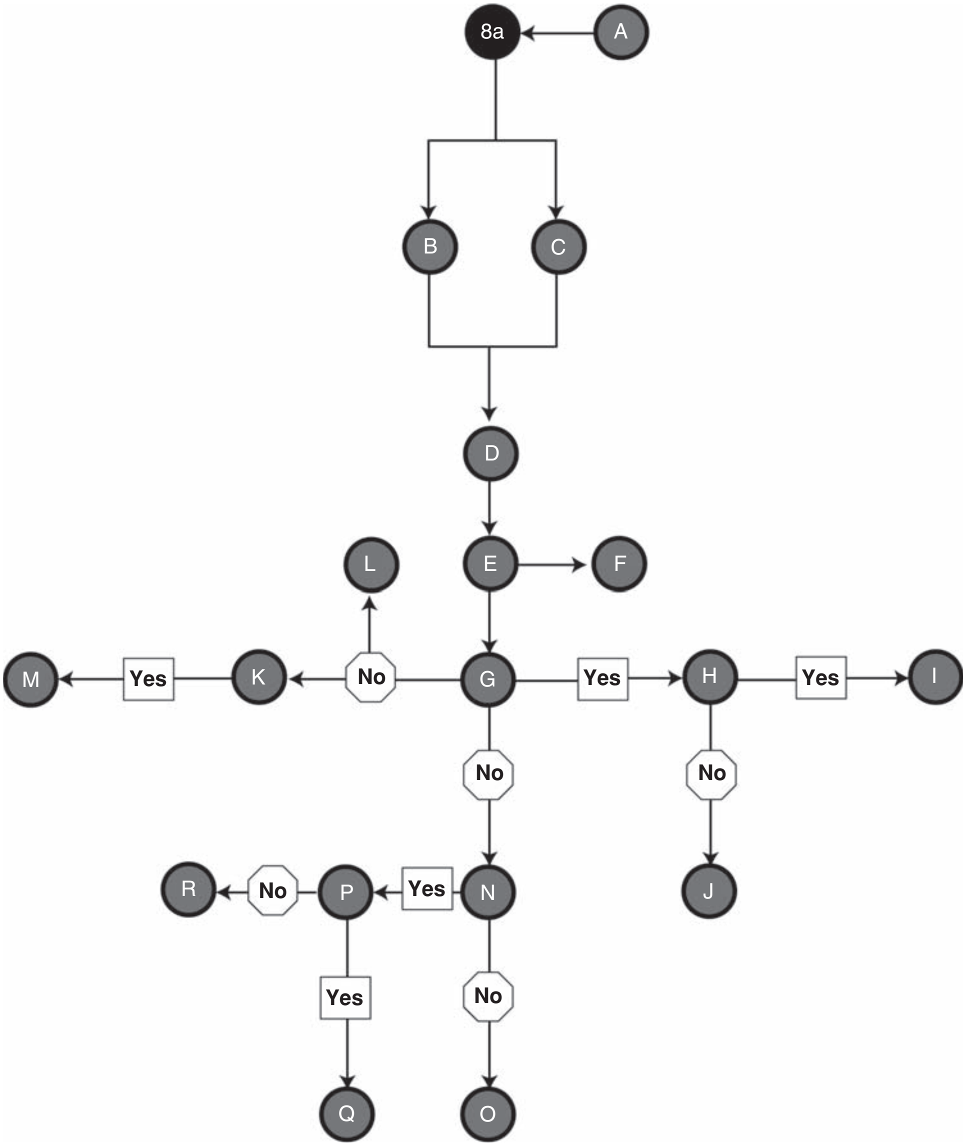


FIGURE 12.23(b)

Graphic representation of decision tree for decision 4.

improve the hydraulics of the PRW should be continued. Monitoring data (water quality and potentiometric) should be utilized to establish DAF values and maximum concentrations acceptable at the City Aquifer boundary with and without pumping at EW-2. Feasibility studies should be directed toward passive techniques (such as phytoremediation) that are capable of increasing the DAF and reducing the contaminant concentrations sufficient to ultimately cease pump and treat activities.

These steps were taken at the Site and a Record of Decision has since been signed. The remedies, which have been implemented, chosen for the Site are monitored natural attenuation of the TCE and institutional controls to maintain industrial land use and prevent use of the groundwater. In the former solvent pit source area, reductive dechlorination via an in situ reactive zone is also being used. Sentinel and monitoring wells continue to monitor for NAPL migration.

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PART III

Introduction to Tools for Sustainability Decision Making

Kandi Brown

Chapters 13 through 19 in this part illustrate the products of innovative thinkers that bridge multiple disciplines with problem-solving abilities that transcend traditional approaches. In this part, the reader will see examples of where the vision of projects is expanded beyond the acute and local to one that is globally and sustainably balanced.

Each chapter provides an in-depth discussion of various technical tools that are used to provide the foundation for Decision Consequence Analysis (DCA). These tools include communication devices to facilitate the transfer of detailed technical information to a variety of audiences, as well as technical approaches to data management and collection, statistical and forensic analysis, and risk assessment. Case studies documenting water conservation on a large scale and carbon sequestration modeling are also provided.

Chapter 13 describes the dilemma between merely collecting versus actually processing and analyzing data. This chapter goes on to describe how Geographic Information Systems (GIS) can be used to store, represent, and process spatial data to determine potential renewable energy sources; assess available biomass; and conduct remote-sensing of multi-temporal imagery. A variety of communication tools that have been applied in the environmental arena, including GIS, are discussed in Chapter 14.

Chapter 15 provides a clear definition of the utility of traditional environmental statistics and uses advanced geostatistics and principal component analysis to clarify data evaluations. Collecting the right data is critical in all situations but it is particularly important in land restoration, where the party responsible for the environmental cleanup must be determined. Environmental forensics, discussed in Chapter 16, can play an instrumental role in defining responsible parties.

Contaminants in the environment do not necessarily pose a risk to human health. Chapter 17 provides a detailed discussion of the mechanics of human health risk assessment and innovative evaluations of short-term risks that are inherent in remediation activities. Chapters 18 and 19 provide detailed case studies related to water conservation and reuse from a mining operation and greenhouse gas sequestering on DoD lands. These chapters speak to the core issues of sustainability—reduced use of virgin materials and exploration of market opportunities stemming from carbon cap and trade.

CHAPTER

Data Management, GIS, and Remote Sensing

13

Michael Wild, Dane Williams, Daniel Smith

13.1 THE DATA DILEMMA

Data are everywhere—in all shapes and sizes, coming from all directions and knocking persistently at our door. The age of information is providing mountains of ever-growing digital data—some data are managed and stored for examination and study; some are easily lost or forgotten. We try to reason that we don't need data from the past; we can always collect more in the future. However, as with history, if we forget or disregard data from the past, we doom ourselves to repeat analyses, waste resources, and squander time.

Somehow, we continue to collect data. Even through lean economic times, we march on and store and post our data for others to see and use. Through the Internet, various entities both public and private provide easily accessible data at little or no cost. We know, just as our ancestors did when they passed down information through oral storytelling or the recording of events on stone or parchment, that the information we collect and maintain today may be useful for future generations. We must remember, however, to examine our data and not just amass and store it.

13.1.1 Assessing Spatial Data Using Geographic Information Systems

Geographic Information Systems (GIS) offer a way to look at data in a spatial context (see Figure 13.1). We abstract or simplify the real world into two types of spatial conceptualizations and corresponding models: the discrete view of objects in space (corresponding to vector representations) and the continuous view of those objects (analogous to raster representations). Vector models use points, lines, and polygons to respectively represent objects such as trees, transmission lines, and parcels of land. These geometric objects can contain a plethora of associated characteristics that in the vector model are traditionally stored as records in

DOI: 10.1016/B978-1-85617-797-9.00013-7

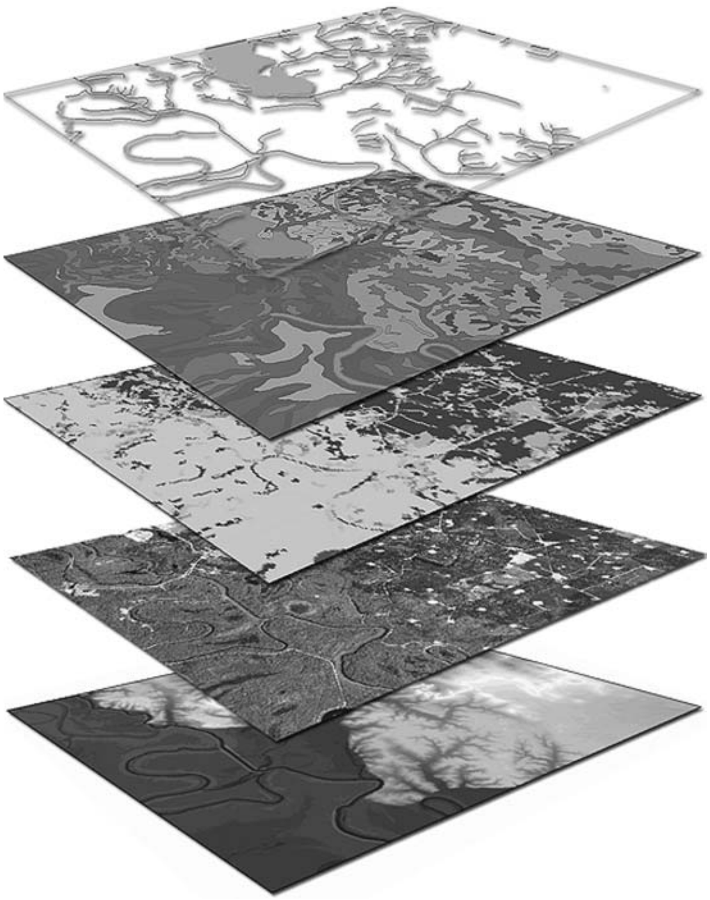

FIGURE 13.1

GIS data: terrain (raster—continuous), satellite imagery (raster—continuous), land cover (raster—thematic), soils (polygons), and water bodies (polygons and lines).

tables. Traditional tabular data can then be linked to these geometric features so that common database functions, such as queries and statistical summaries, can be seen graphically on a map.

Vector representations are appropriate for data sets having an explicit spatial location. Roads, for example, are better represented as discrete vector data because they have an explicit location and existence; they rarely taper off into nothingness. Additionally, most people do not care where roads are not; they only want to know the fastest and easiest way to pick up groceries and drop off the kids.

Thematic raster data models further abstract the real world into continuous arrays of cells or pixels. Each cell contains a discrete value demarcating whether or not (or how much of) the objects or phenomena of interest exist at a given location. A thematic raster representation of data may be more appropriate in situations where all locations within a spatial extent have a discrete meaning, such as a land cover data layer where each pixel in the array has a discrete classification category. A good example of a continuous raster representation is a terrain model, where each pixel represents a vertical elevation value. Photography, satellite imagery, and the like are also examples of continuous raster representations in which the pixel has a value. However, these pixels may not have discrete meaning until further analyzed using image processing techniques. Multi-spectral raster representations are simply a stack of raster representations, with each layer representing a discrete range of spectrum or other calculated values.

Many years ago, there was great debate in the GIS realm as to whether vector or raster representations of data were better. This debate has virtually disappeared because GIS analysts and data managers now understand that there is a technical place for both and that, depending on the data being represented and the task at hand, one format may better represent the information.

13.2 DATA MANAGEMENT, GIS, AND SUSTAINABILITY

Technology has made an undeniable impact on our world. It has improved our health, expanded our population, and maximized our use of available resources. However, these same improvements are also detriments in terms of the health of our planet. So far, we have not achieved a sustainable balance. GIS and sound data management are important components of sustainability. Whether they are used to justify socioeconomic decisions, determine the feasibility of renewable energy sources, or assess environmental degradation, GIS and data management will play a key role in shaping our world today and in the future. The following sections discuss such applications.

13.2.1 Optimizing Location-Specific Renewable Resources

We have become an energy-dependent society. Energy has a place in every facet of our lives, and its use is growing exponentially, especially in developing countries like India and China. Large and reliable amounts of energy are required to fuel global development and growth. However, energy derived from fossil fuels is undeniably finite and has been shown to be harmful to the environment during harvesting, manufacturing, and use. Renewable energy (RE) is a long-term, sustainable solution.

GIS can also be used to further RE technologies. For example, we can use GIS to determine where to construct biomass power plants with reliable fuel sources or the optimal placement of wind turbines. To accomplish such analyses, multiple spatial data sets must be combined using specialized analysis tools. First, for thorough and accurate answers, we need the appropriate data represented with the appropriate data model. Second, we need an understanding of the tools and principles of data analysis. Third, we need the ability to represent and communicate the results of our analysis. A brief example of how GIS was used to identify the location for potential biomass projects in Georgia is discussed in the following paragraphs.

Determining the Location-Specific Potential for Biomass Projects

According to the National Renewable Energy Laboratory (NREL, n.d.), biomass is plant matter such as trees, grasses, agricultural crops, or other biological material. It can be used for fuel in its solid form or can be converted into liquid or gas and used to produce fuels, electricity, heat, and chemicals. Globally, biomass is currently the fourth largest producer of energy behind classic fossil fuels such as oil, coal, and natural gas. Researchers estimate that there are 278 quadrillion BTUs of installed biomass capacity worldwide (NREL, n.d.). With such a wide variety of possible sources and great potential over such a large area, tools and techniques are needed to locate biomass resources and possible production facilities efficiently and effectively.

The state of Georgia is a prime candidate for biomass development, with approximately 23,000,000 acres that could qualify as biomass stock. Many tools and techniques were available for resource and facility site identification in the state. This case study presents one technique: an additive model used to combine environmental and infrastructure parameters to determine locations that had viable amounts of biomass resources and that were suitable for biomass energy facility construction.

Data Acquisition

The first step was to identify data needs. Discussions with foresters and research into biomass identified the following critical data sets:

Land cover type. Land cover types, and proximity to certain land covers, in many ways dictate biomass potential and a location's potential as a biomass facility site. Forested areas and agricultural lands provide more biomass feedstock than, say, an urban environment. Land cover data from the National Land Cover Database consisting of 29 land cover classifications was used for this project (MLRC, 2001). It was recoded into ten classes of interest by combining similar class types (e.g., medium and heavy urban).

Percent tree canopy. Percent tree canopy data was used to quantify biomass and open space availability. Areas with a higher percent of tree canopy likely have elevated amounts of biomass in accordance with accepted biomass definitions. (Agricultural and grasslands have higher amounts of biomass as well, but these features were characterized in the land cover data set (item 1).) Conversely, areas with a lower percent of canopy and adjacent to a higher percent of canopy are better for biomass facility construction because of their available resources.

Biomass resource potential. Biomass approximations by county were used to quantify seven biomass feedstock categories: crop residues, methane emissions from manure management, methane emissions from landfills and wastewater treatment facilities, forest residues, primary and secondary mill residues, urban wood waste, and dedicated energy crops (NREL, n.d.). Because these data are at the county level, it gives general locations for potential biomass projects but nothing more granular. It was created using methods accepted by the NREL.

Proximity to high-voltage power lines. As one of many infrastructure parameters that could assist in modeling suitability, proximity to high-voltage powers lines was chosen for site scoring because it provides a means for the power generated by biomass facilities to be put into the grid. This data set represents general locations of 115-, 161-, 230-, and 500-kilovolt power lines in the United States developed by the Federal Emergency Management Agency (FEMA). Data sets on the general location of high-voltage power line are available from NREL (2005).

These are just a few of the data sets that could be used in identifying locations for biomass projects in Georgia. Additional data sets of interest include road data, community tapestry data, species data, and land ownership/cadastral data, to name a few. Consultation with domain specialists is always recommended when modeling biomass site potential or other natural phenomena, to define essential variables, contributing factors to phenomena, and model parameters.

Analysis

Combining data and the method used to do so make analysis interesting. The answers we derive from the analysis make it useful. To determine site potential for biomass projects in Georgia, a simple additive approach was taken that ranked all locations based on summation of the respective parts (in this case the scoring of each aforementioned data set). The following paragraphs document the procedure.

The data sets not natively in raster format (specifically power lines and biomass potential at the county level) were first converted to raster in order to return a scoring at all locations in the study area (continuous across the state). The FEMA high-voltage power line data were buffered before conversion to raster using a multi-ringed buffer to provide varying proximities to power lines with which to score potential sites.

Once all of the data sets were converted, recoding of the data was performed. This was essential for two reasons: (1) Since NLCD data (land cover class data) are inherently nominal, mathematical computations on it were not possible; and (2) for the additive approach used, a common, "real" zero value was needed to rank specific locations as better or worse than other locations. The recoding procedure consisted of grouping values and then, in this case, giving the grouped values a score (a recoded value) that corresponded to their rank. Each input data set was recoded into 10 classes and scored sequentially from 1 to 10. Recoding required research and consultation with domain specialists to ensure that proper consideration and values were given to input variables.

After all the data sets were recoded, coincident raster cell values were summed to produce the final site potential score (Figure 13.2). Once summed, a data set scoring all locations in Georgia as to site potential for biomass projects ranging from 2 to 40 was generated. Once the data were responsible and cartographically represented, it could then be used by decision makers and developers to assist with biomass facility placement.

Case Study Summary

Spatial analysis (and the maps derived from it) gives policy makers and energy professionals a tool to make informed and well-rounded decisions about a wide variety of issues. This analysis illustrates how a stepwise and additive GIS analysis can help answer spatially complex and data intensive questions.

What Qualifies as Renewable Biomass?

As mentioned earlier, clean and efficient energy is vital to our interests. The effects of legislative policy decisions can, however, be hampered by a limited understanding of available data. The 2007 Renewable Fuel Standard (RFS) Energy Act is a case in point.

The RFS restricted the use of timberland-based biomass for renewable fuel to privately held lands that were already managed plantations. These plantations currently provide raw resources for wood, pulp, and paper products. Most of the industries that use timber require high-quality materials and so discard lesser-quality materials. Consequently, much can be wasted during harvesting. Non-plantation lands also waste biomass as part of routine forest fire protection, clearing for residential and commercial development, and forest ecosystem health programs that clear brush and thin out small-diameter trees.

Obtaining energy from biomass is not so particular. Waste materials that cannot be used elsewhere can be burned for energy or converted to cellulosic ethanol. According to the 2007 RFS, the lands available for these materials are narrow and sparse. However, this is not an accurate representation of biomass availability. In fact, land ownership holdings compiled by the U.S. Forest Service (USFS) can be used to approximate the true availability of other non-plantation lands for woody biomass. The first step is to mine the data.

Tabular Biomass Data Mining

The USFS has been managing public lands in national forests and grasslands since 1905. It also maintains bibliographic and archival databases for both federal and privately held lands (USFS, n.d.(a)). The USFS's Forest Inventory and Analysis

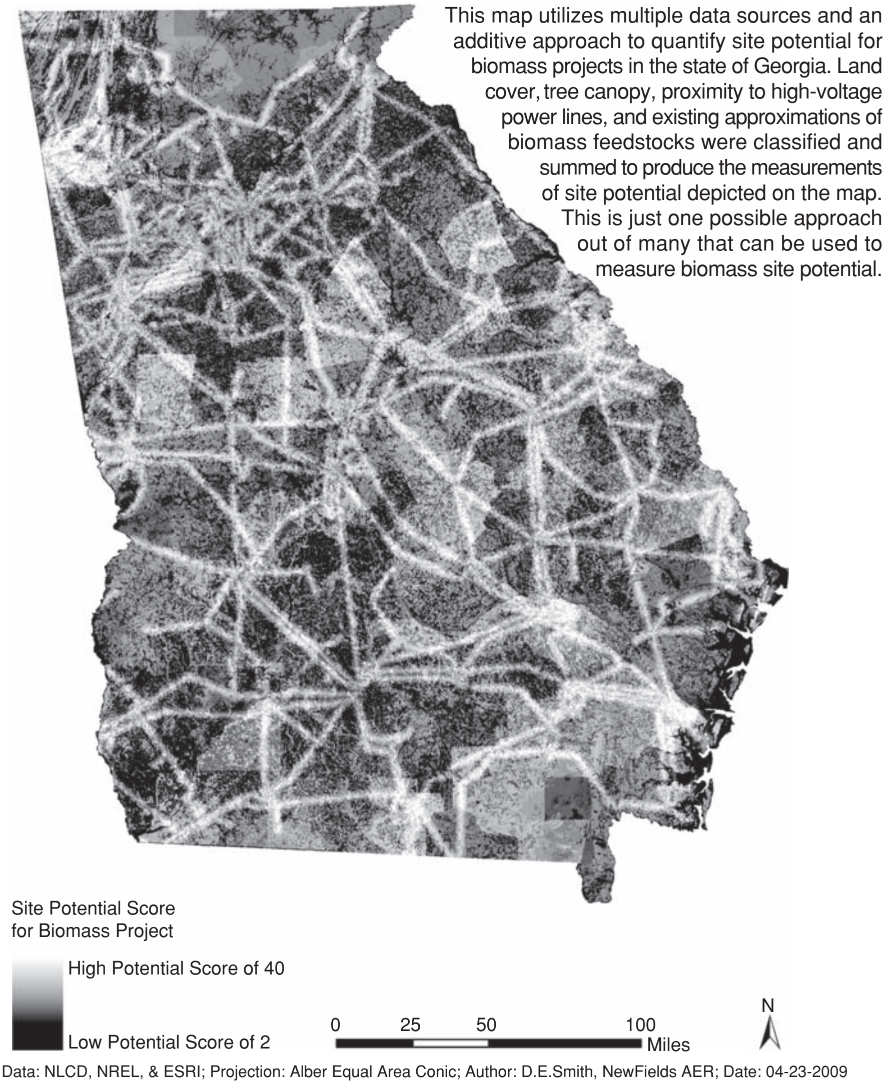

FIGURE 13.2

Site potential score. Biomass project site potential for the state of Georgia.

(FIA) Program (USFS, n.d.(b)) provides information about America's forests. According to the USFS Web site, the FIA compiles and reviews trends in forested land in terms of area and location; in species, size, and health of trees; in total tree growth, mortality, and removals by harvest; in wood production and utilization rates by various products; and in forest land ownership.

The FIA Web site allows users to download USFS inventory data as state-specific extracts of the FIA database. (The complete FIA database is unavailable online because of file size constraints. For instance, the size of Michigan's inventory data for the most current year is nearly one gigabyte.) If a user is interested in a multi-state analysis, each state's database must be individually downloaded and the desired tables appended to one another. Because each state's database is in a well-defined format, queries can be developed to easily append the selected fields into non-state-specific or common tables. Once the data has been culled, processed, and compiled, more queries can be developed to analyze the available information. Since the inventory data for all desired states is in one table, these analyses can be performed once rather than state by state. Figure 13.3 shows timberland acreage for select states.

Based on FIA data, the 2007 RFS Act limits the use of any type of woody biomass, even ground cover, leaves, or invasive species, to a fraction of available timberland. This Act limits what qualifies as biomass to, on average, less than 9 percent of available timberland for the selected states shown in Figure 13.3. Some states have zero acres available for use as renewable energy, even though they have millions of acres of timberland.

Although the actual numbers shown in Figure 13.3 are compelling, the presentation of this information is not. Here is where GIS can step in to help accurately describe the spatial impact of the FIA inventory data.

State	Total Acres	Non-Federal Acres	Privately Held Acres	Privately Held Plantation Acres
Minnesota	15,414,217	13,338,838	7,189,173	267,936
Louisiana	14,035,007	13,129,288	12,411,414	4,120,591
Tennessee	13,450,287	12,495,336	11,829,162	636,008
New Hampshire	4,539,573	3,855,009	3,441,767	8,465
Vermont	4,479,744	4,078,205	3,764,381	16,541
New Mexico	4,359,872	1,530,708	1,411,160	0
North Dakota	500,213	426,536	382,664	4,174

FIGURE 13.3

Timberland acreage for select states.

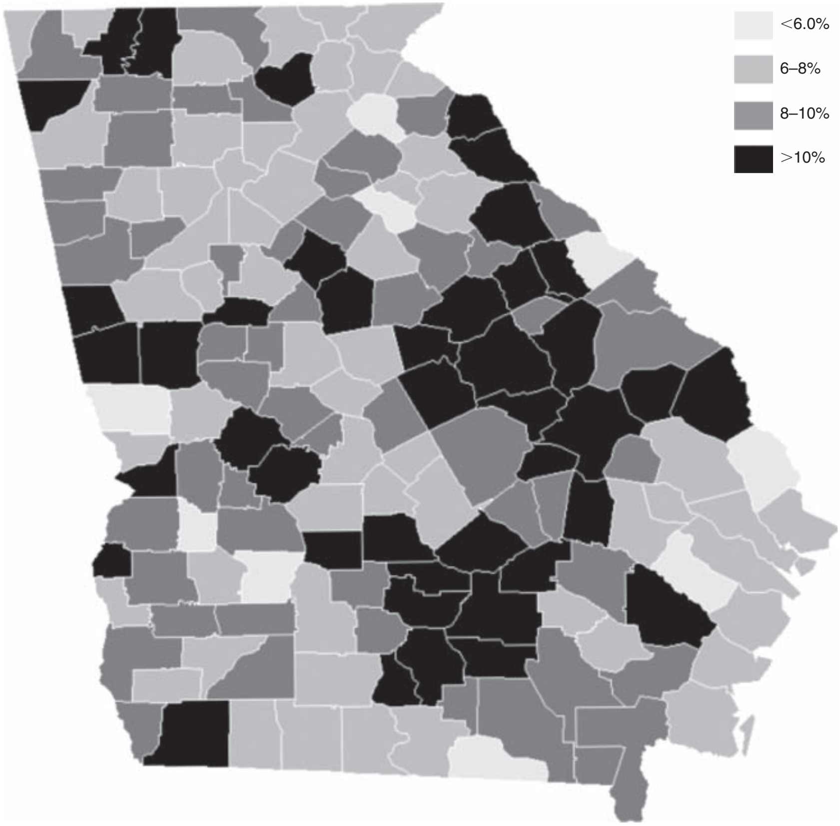

FIGURE 13.4

Georgia unemployment rates from December 2008.

Spatial Analysis of Biomass

The FIA data are compiled on a county level. By matching the tabular data for each county to the polygon that represents it, we can obtain a sense of the spatial distribution of timberland acres.

Thematic maps offer one of the simplest ways to display vector-based spatial data. They show geographic patterns, such as population statistics, by color-coding ranges of values. As an example, Figure 13.4 demonstrates 2008 unemployment rates for each county in Georgia due to a nationwide economic recession.

Timberland acreage amounts can also be shown by county with a thematic map. However, county-level data can oversimplify timberland by ignoring the age, density, distribution, and diversity of trees. Such information can be harvestable timber or undergrowth on federally owned and managed national parks and military bases. Satellite imagery can be used to map the actual tree canopy of certain species, displayed as raster data, which can then be compared to polygonal vector data such as federal land holdings, as shown in Figure 13.5. However, although Figure 13.4 clearly demonstrates that most of Georgia is heavily forested, it does not allow us to see the limitation of the 2007 RFS Act to only privately held plantations. Obtaining data on ownership of individual parcels of land is technically possible, but accurately compiling an entire state's worth of cadastral data is infeasible.

Instead, we can visualize the placement and concentration of timberland using dot density maps. Such maps represent not actual locations of trees but the total number of timberland acres available for biomass management in each county. These representations can be limited to areas in each county based on overlapping

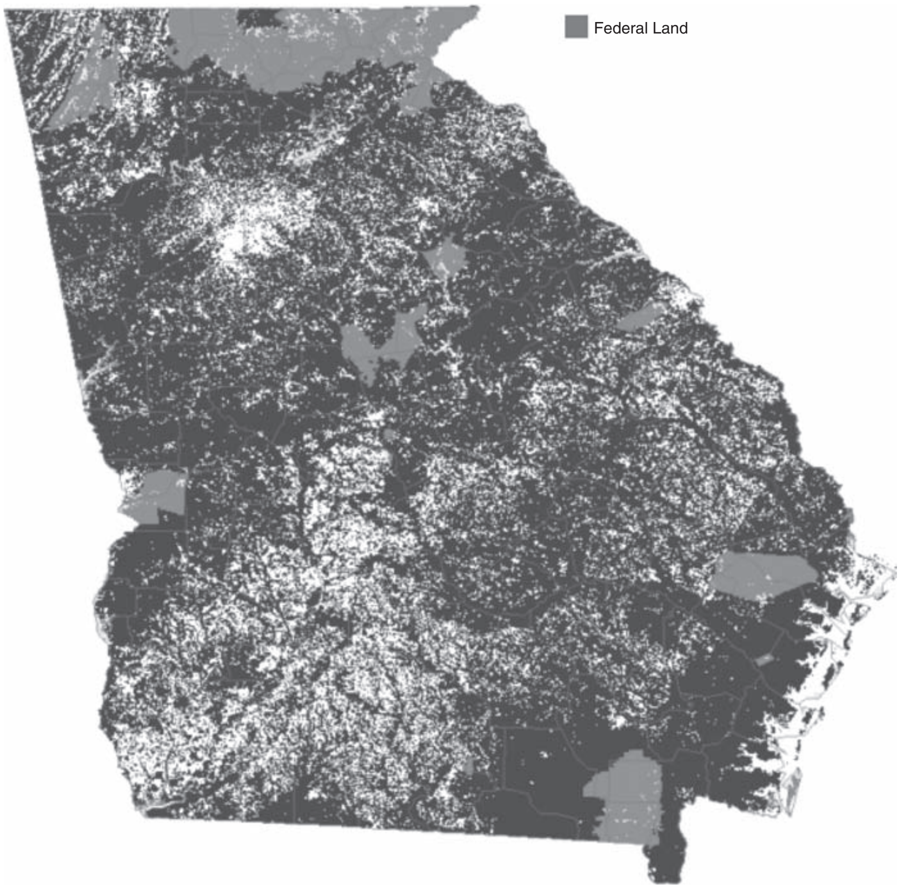

FIGURE 13.5

Raster representation of Georgia timberland.

vector information, such as federal lands, water bodies, and marshland. An example of this type of visualization is shown in Figure 13.6, which displays total timberland acres per county versus privately held plantation or artificial acres for Tennessee.

Visualizing the data in this way makes the limitations of the 2007 RFS Act become abundantly clear. In fact, maps similar to the one in Figure 13.6 were used to demonstrate this limitation to Congress in March 2009. A draft of the American Clean Energy and Security Act of 2009 (ACES) now corrects what the 2007 RFS definition of available woody biomass had wrong. ACES was sponsored by Representative Henry A. Waxman, chair of the Energy and Commerce Committee, and Representative Edward J. Markey, chair of that committee's Energy and Environment Subcommittee. The Waxman-Markey bill contains a compromise on the definition that allows some noncommercial biomass to be removed from federal lands to prevent forest fires or to manage forest health. This compromise recognizes that sustainable forestry practices can coincide with proper use of renewable energy resources.

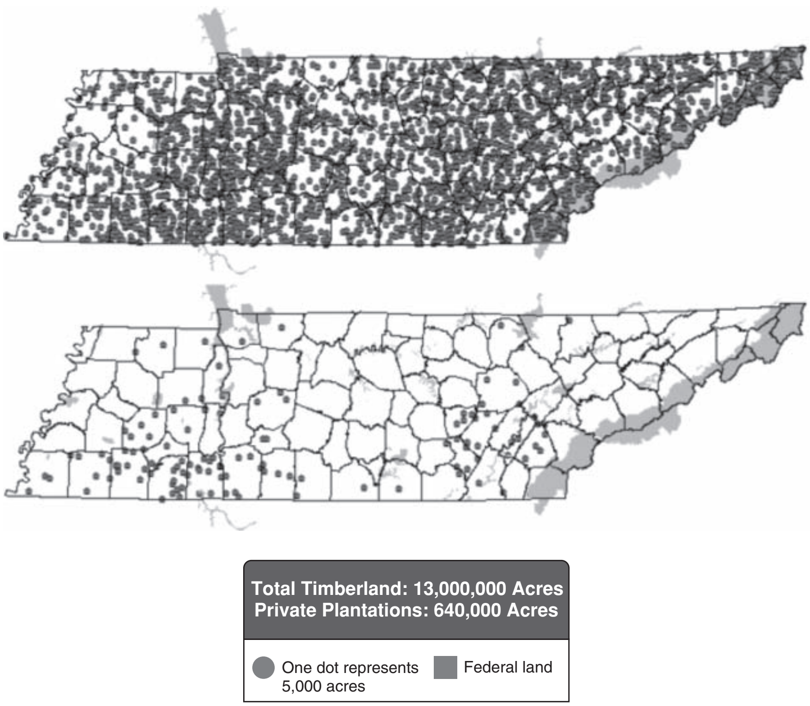

FIGURE 13.6

Tennessee timberland qualifying as "renewable biomass."

13.3 REMOTE SENSING: IMAGE OF INNOVATION

Remote sensing is the science and art of gathering data from a location physically removed from the Earth's surface and then analyzing and scrutinizing that data. It is an often misunderstood technology victimized by over-ambitious expectations. However, it is more often underutilized, much like the massive quantities of data gathered during the cleanup of environmentally impaired properties, of which only a small fraction is used to make calculated decisions.

Remotely sensed imagery provides a snapshot of time and space that represents conditions never to identically exist again. Long before the Scottish landscape architect Ian McHarg contributed to the concept of GIS in the 1960s through his use of map overlays, remote sensing existed in the form of aerial photography. Early aerial photography projects offered a vast temporal range of remote-sensing data. In fact, many of them have been digitized and are readily available through online repositories such as the U.S. Geological Survey. Such photographic records serve only as a raw information source not yet subjected to interpretation resulting in the polygons, lines, and points of a GIS or map. Still, the amount of information they store is huge and, given the proper creative application, has the opportunity to provide immense value to an existing GIS. Such imagery can also offer the opportunity to begin construction of a new GIS database from extraction and discrimination of its stored image features.

A single remotely sensed image may be interpreted from multiple application vantage points, with resulting interpretations supporting a range of purposes and disciplines such as identifying vegetative stands for the ecologist, agricultural crop vigor for the agronomist, residential construction extent for the urban planner, fault lines for the geologist, and impervious surfaces for the engineer. This interpreted data may be powerful, but the fodder for that interpretation is the remote-sensing imagery itself.

Most often, remotely sensed imagery is acquired from an airborne or satellite platform at a near down-looking "on-nadir" angle that offers simple integration of extracted data into a GIS decision-making system. Traditionally, it is defined by four types of resolution: spatial, spectral, radiometric, and temporal. These imagery characteristics provide a quick understanding of the viability and applicability of the data produced. An idealistic image has an infinite depth of spatial resolution with continuous zoom and refined detail at every scale; wide and granular segmentation of the electromagnetic spectrum such that actual spectral reflectance curves can be represented by the imagery source at the pixel level; and radiometric data bit depth such that no information is lost in data formatting and storage. Lastly, the temporal resolution of the imagery is a continuous, real-time feed.

However, although an image source can serve as reference and fodder for any application imaginable, it is purely idealistic because of imaging science, data transfer, data storage, software, and financial limitations.

Reality dictates that we select an imagery source that is customized to our application. Imagery products range in spectral resolution from panchromatic (black and white, representing a broad range of the spectrum, such as the visible portion, to multi-spectral (e.g., separate bands for red, green, blue, near-infrared, etc.) to hyper-spectral (hundreds of bands, with each representing a narrow slice of the spectrum). Spatial resolution ranges from inches to many miles per pixel. Temporal resolution ranges from one time only to daily. Methods of interpretation have evolved from acetate overlay delineation to delineation in a 3D/photogrammetric environment to pixel-based imagery discrimination to object-based imagery segmentation.

During the spatial project planning stage, consideration must be given to the information necessary for the decision-making process. The decisions that need to be made will dictate the sources of information required to populate the database upon which analysis will be applied.

Imagery sources must be understood and selected appropriately. For instance, remote-sensing imagery is incredibly valuable for extracting land *cover* types (coniferous forest, deciduous forest, agricultural fields, open water, etc.), but it cannot discern certain land *use* types, such as whether a structure serves a residential or commercial function. The physical size of the features to be interpreted must be understood such that the scale of the imagery (spatial resolution) is appropriate for proper feature discrimination. Temporal characteristics, such as season acquired, may also significantly affect the resulting classification. One example is the discrimination of specific agricultural crops, which are controlled by a farmer's crop calendar; another is an impervious surface delineation, which is best accomplished using imagery acquired during leaf-off conditions.

Such understanding provides the basis for articulating both remote-sensing and ephemeris data needs in order to develop a database capable of supporting decision making. Land managers, tax commissioners, environmental compliance regulators, farmers, and other decision makers too numerous to mention may all benefit from robust analysis of remotely sensed imagery, the science of remote sensing.

13.4 DISCIPLINE-SPECIFIC REMOTE-SENSING APPLICATIONS

The following subsections detail several examples of remote-sensing applications as applied to specific disciplines.

13.4.1 Land Management

Fully understanding current conditions, trending patterns, and potential threats facilitates fully informed land management decisions. Monitoring land area through multi-temporal imagery analysis allows proactive identification of areas of change, no matter how subtle a change may be. Figure 13.7 shows an example of how remote-sensing applications can be used to identify the effect of a 2003 forest fire on the landscape by delineating the areas affected by the fire as well as those of reestablished vegetative growth.

Remote-sensing applications can also be used to periodically monitor invasive species, which is neccessary for proper land management. Invasive species monitoring by remote sensing discriminates the vegetation of concern from periodic

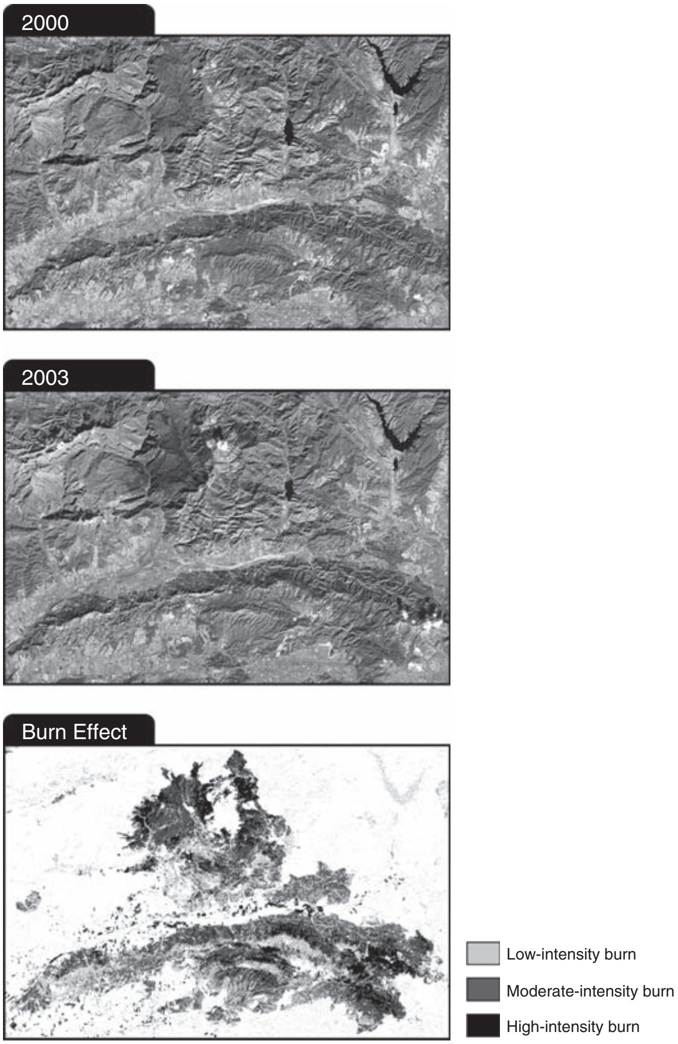

FIGURE 13.7

Time series analysis of forest fire effects on the landscape.

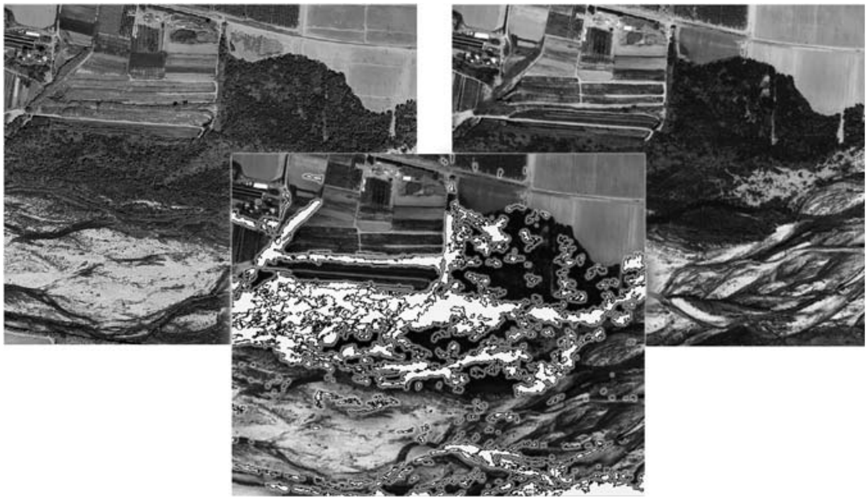

FIGURE 13.8

Periodic monitoring of invasive species intrusion.

imagery collections. Even more beneficial is the use of time-series delineation data along with several other GIS data layers to establish an invasive species forecasting model that identifies areas prone to infestation. Figure 13.8 shows an example of this type of analysis.

13.4.2 Urban Planning

Updating basemap data for a county or municipality is a costly venture. Through multi-temporal imagery, screening is possible to readily identify areas of development. This can help focus basemap information updating. A similar methodology at a higher resolution can identify physical improvements to property that may have property tax implications.

Forestry monitoring also benefits from such applications to confirm reported timber removal. This relatively low-cost screening may have major implications in urban planning decision making and in ensuring proper accounting for land-based taxable activities. Figure 13.9 shows how changes in development patterns may be detected using remote-sensing applications.

13.4.3 Agriculture

Remote-sensing imagery and analysis are used to monitor crop health throughout the course of a crop calendar. One example is identifying areas with performance

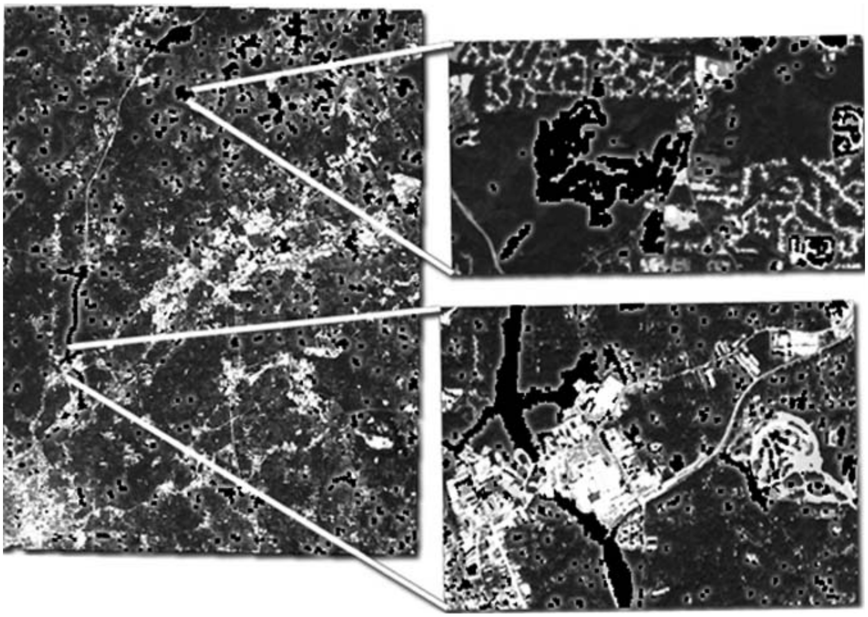

FIGURE 13.9

Five-year change detection out to urban development.

FIGURE 13.10

Remotely sensed imagery for agricultural analyses.

issues due to soil conditions or pest effects; another is tying derived vegetative indices to field-collected calibration data to determine yield performance for a given crop. Remote sensing allows monitoring of potentially vast land holdings in a manner that is simply not feasible with traditional field-based methods. Figure 13.10 is an example of this use of remotely sensed imagery.

13.5 CONCLUSION

Compiling, managing, and analyzing information using databases and other data management tools are fairly straightforward. We decide what types of information we want to look at and how we should store that information. Whether information comes from oceans, land, air, or space, we can process and test it in new and traditional ways. Geographic Information Systems and remote-sensing applications, along with standard database software, offer dynamic and innovative ways to analyze, process, represent, and manage spatially related data. The key to making the best use of the plethora of data available today is to keep looking, keep mining, and keep analyzing.

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CHAPTER

Communication Tools

14

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The recognition and selection of appropriate communication tools can be tremendously effective in helping a group of diverse stakeholders meet their shared objectives. Because each individual comes from a different body of knowledge and a different skill set, it is important to appeal to people across all learning styles as well as to deliver a message that is technically scalable to the various levels of expertise involved in environmental restoration. It is a challenge to provide technically robust and defensible information in a visually appealing, concise, interactive, and useful format. However, forethought in such message delivery and consideration of all levels of an organization or group throughout every stage of environmental restoration will advance the goal of effective project completion.

As projects progress and stakeholders continue to convene over decision points, traditional communication tools—generating agendas (and adhering to them, unless the group votes otherwise), documenting meeting discussions, making referenced documents available to the group online, and checking in with the group for feedback on the overall decision-making process—allow team building and involvement from stakeholders. In addition to these traditional practices, this chapter presents innovative approaches to group communication, addressing ways to handle cumbersome data sets or lengthy technical reports.

14.1 COMMUNICATING WITH GIS

As discussed in the previous chapter, GIS is not just a tool to make pretty pictures. It is a powerful analytical and decision-making tool. GIS can also be used to interactively convey complex information and data within a group setting to establish and maintain consensus. It is robust in its database capabilities, as well as in its ability to objectively frame baseline conditions within a dynamic system.

Although initial data processing and formatting of the various layers can be somewhat involved, once a GIS is built, navigation and data exploration are fairly straightforward and allow for a holistic snapshot of what is happening on a site presently, historically, and potentially moving forward. As a means for

DOI: 10.1016/B978-1-85617-797-9.00014-9

transforming massive amounts of data into useful information, GIS can dispel the perception of risks or uncertainties with a complete and objective view of the site. It allows the group, as a team, to identify data gaps as well as to understand existing and historical site conditions. In this way, GIS can be a decision support and consensus-building tool from the project initiation and problem-framing phases all the way through to site closure and project completion.

Consider as an example a water district in need of developing a maximum flow level (MFL) for a first-magnitude spring in northern Florida. The spring is one of only three large, natural warm-water winter refuges for manatees. Because of increased development, groundwater withdrawals had increased, contributing to cold-water intrusion into the spring. The water district was mandated to protect the manatee to ensure that not a single one would be harmed. As a result, environmental organizations, regulatory authorities, developers, and utilities became involved in the development of the MFL for the spring so that their various interests could be represented.

For more than 30 years, a local park ranger had collected data on the spring in a log book, recording the location of the manatee as well as the water temperature and depth. These data were essential to the development of the MFL, but the logbook format made it impossible to evaluate the thousands of data points associated with specific geographic locations. To calculate the carrying capacity of the spring and develop an MFL while maintaining consensus toward progress among a diverse group of stakeholders, a GIS was developed from the park ranger's data (Figures 14.1

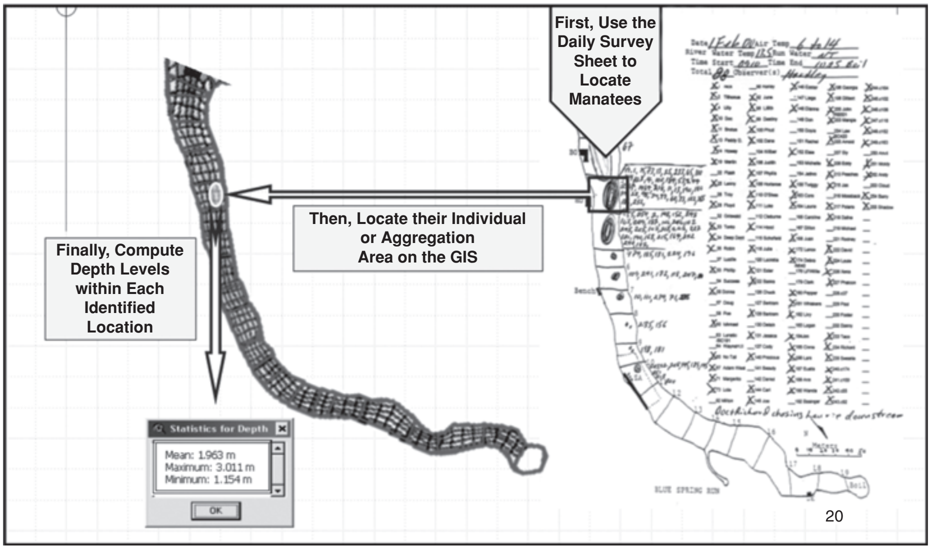

FIGURE 14.1

Representation of field log in GIS for an analysis of an individual manatee habitat: example of depth computations.

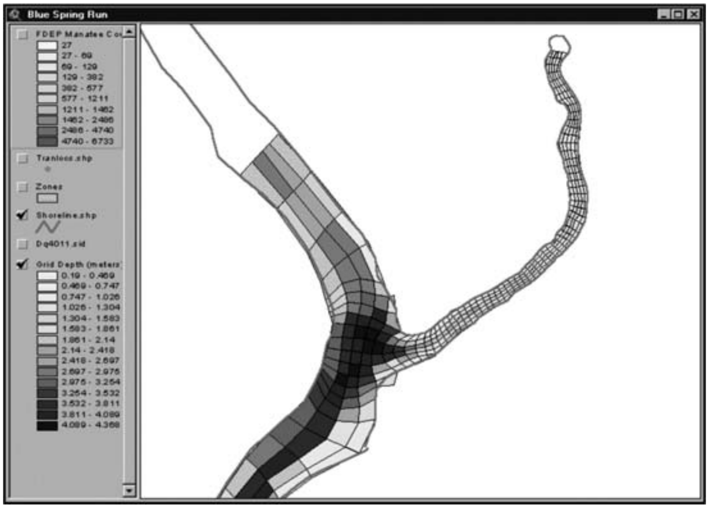

FIGURE 14.2

Visualization of calculated spring capacity in GIS.

and 14.2) that allowed analysis of temporal trends in temperature, depth, and manatee population. As a result, an MFL was successfully developed, and the GIS is now used to periodically assess conditions and review regulatory criteria.

WebGIS has been used to engage members of the general public who may not have access to the meetings where decisions impacting their lives are being made. Utilizing a Google Maps interface, the WebGIS format is very user-friendly and is accessible via the Internet. If a project Web site has been established, interested members of the public may access it, interactively explore WebGIS, and provide feedback to project decision makers. WebGIS engages the public, providing an easily accessible, instantaneous, and potentially anonymous forum in which the public and the project team can interact.

Figure 14.3 shows a WebGIS developed to support communication among project team members for managing a large investigation and remediation of over 10,000 lead-contaminated residential properties. The WebGIS and the supporting Internet-accessible project library (shown in the figure) served to diffuse public antagonism throughout the project. The public was actively engaged in the process through its access to all project-related documents, as well as through a forum in which it could participate in decision making and provide feedback.

14.2 BRIEFING DOCUMENTS

Once the baseline conditions for a project have been assessed and agreed on, decision points have been clarified, and paths forward have been defined, a report is generally written to provide background, summarize findings, and document

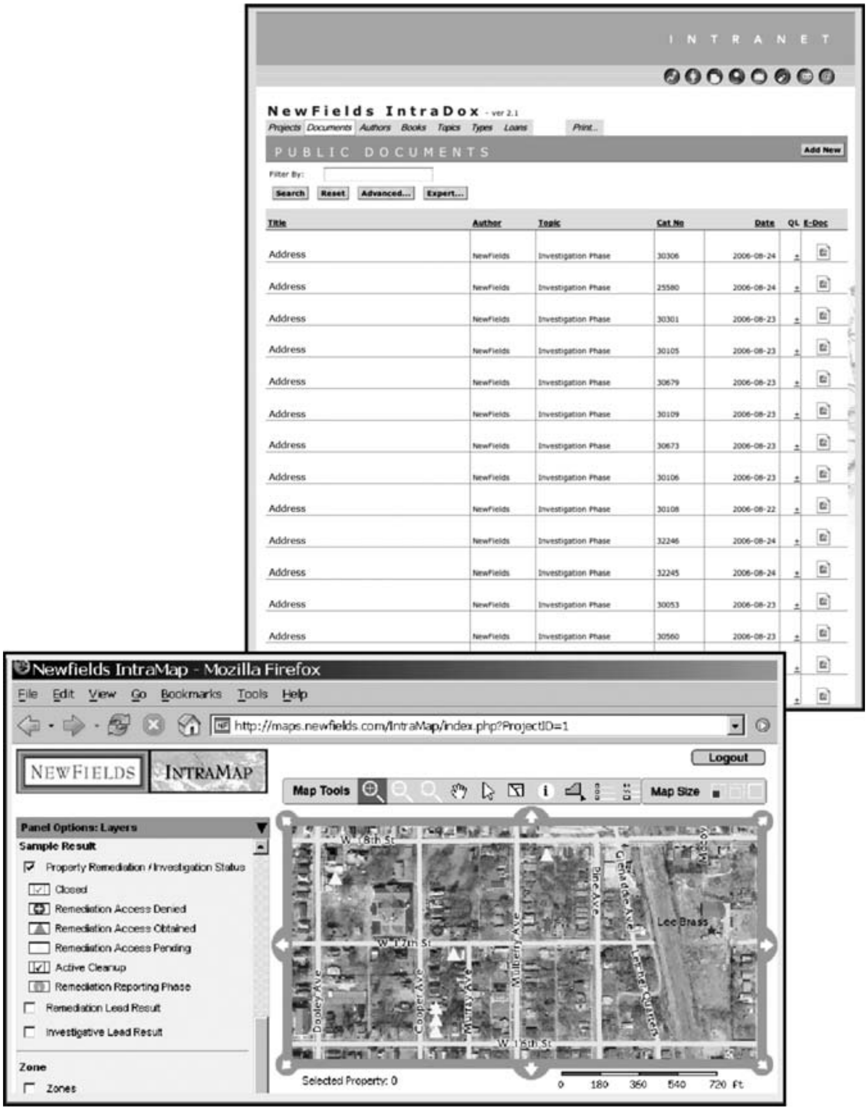

FIGURE 14.3

Example of Web-based GIS and data library.

the next steps. To this end, a briefing document format has been developed as an alternative to the traditional technical report. The concept behind the briefing document was the realization that when an individual reads something, she typically draws a picture in her mind of what is described. To make sure that accurate pictures are drawn, graphics are provided to illustrate the point being made.

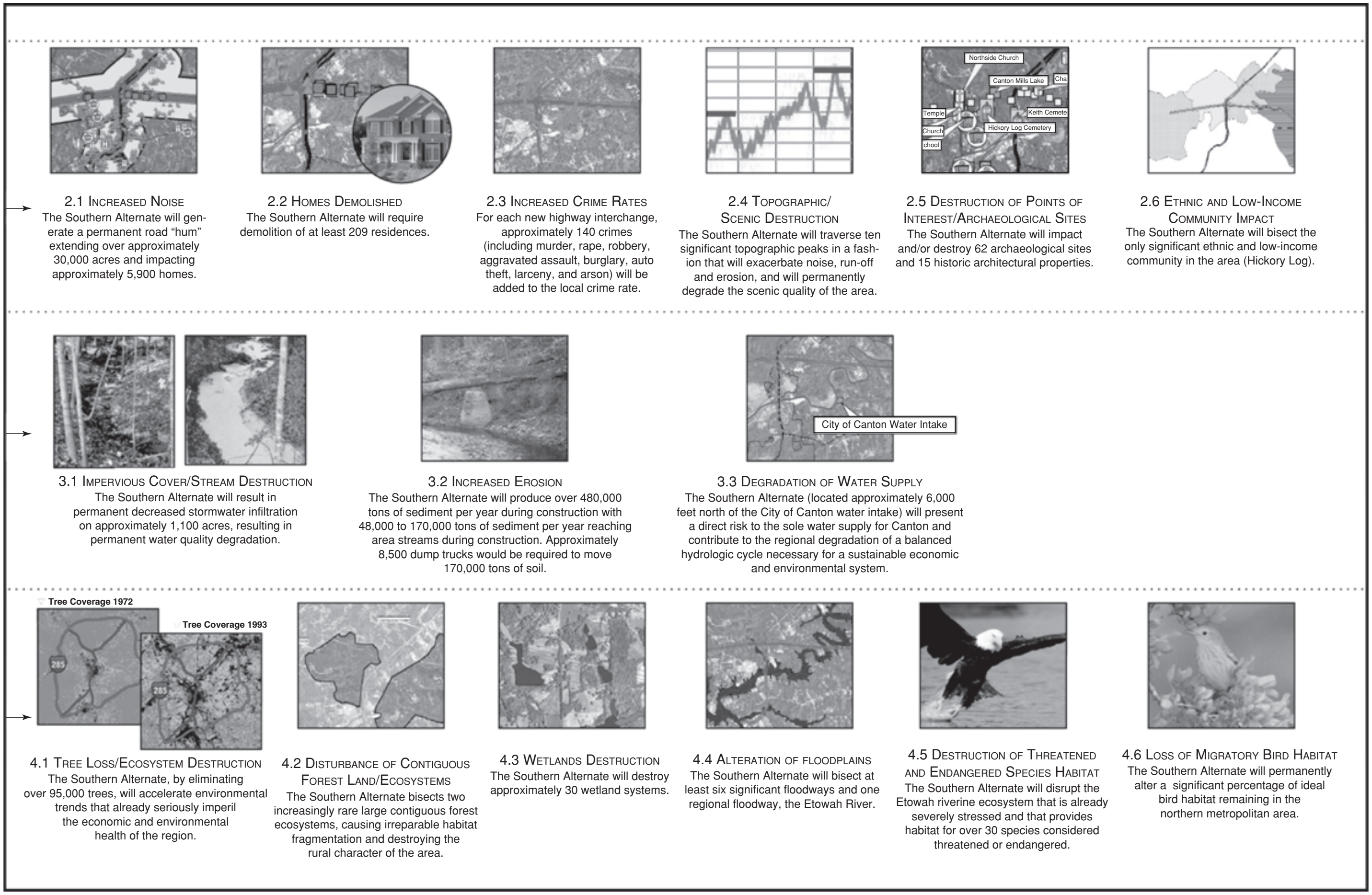

FIGURE 14.4

Example of briefing document summarizing environmental impacts of highway construction project.

Consistent with the motto “A picture is worth a thousand words,” this approach has proven very successful in communicating a technical document’s message to upper management, judges, jurors, advocates, and stakeholders. The briefing document format permits someone unfamiliar with the technical aspects of a project to understand the main issues in thirty to forty minutes. A CEO of a company is unlikely to read a 400-page technical document on site investigation, risk assessment, or feasibility, but he may read an interesting summary of the main issues with illustrations that put those issues in context if he can do so in less than an hour.

Condensing a technical message into a briefing document requires identifying and focusing on the essential issues. A very concise statement with few words is generally much more difficult to write than a long description, but a potent, graphical message with minimal text has proven to be better received by a broad range of audiences.

Figure 14.4 is an example of a briefing document developed for a site in Georgia where a corridor study for the Georgia Department of Transportation (GDOT) was evaluating the need for east–west transportation improvements in Bartow, Cherokee, and Forsyth counties. One town along the corridor conducted an analysis to determine and summarize the community impacts the construction would create. A briefing document to present the situation to residents and the GDOT was developed. As a result, construction was delayed and an alternative plan was developed.

14.3 CONCLUSION

Effective communication is the cornerstone of any successful project. Appropriate communication tools should be evaluated and developed at every project phase to ensure that stakeholders are informed and involved in decision making. The target audience for project information must be identified and appropriate communication tools selected to present information so that it will be readily understood. Different communication tools may be necessary to communicate the same information to different audiences, with the goal being to make technical information universally understandable. In the words of Albert Einstein, “If you can speak of technical things only in technical terms, you do not understand them.”

CHAPTER

Environmental Statistics

15

Brian Wellington, Shahrokh Rouhani

15.1 BACKGROUND

Environmental data by their nature are heterogeneous, complex, and voluminous, and variable in both time and space. Analysis of such data requires its summarization into a form that lends itself to decision making, through development of parameters that describe the data, identification of patterns and trends, and analysis of potential relationships among the parameters. Through this process, environmental statistics can be used to better understand complex data sets and to support decision making.

Statistical applications are a powerful tool suitable for site analysis. This chapter describes some of the techniques available for the statistical analysis of environmental data, including those for summarizing the data, analyzing trends, and comparing different populations. Also described are geostatistical methods used for analyzing data.

15.2 RANGE OF TOOLS

This section provides an overview of methods and statistical tools, including univarite, multivariate, and geostatistical tools that can be used to analyze environmental data.

15.2.1 Univariate Statistics

Univariate statistics is the analysis of measured or assigned values of a single variable. The analysis of such data is performed to (1) compute summary parameters, (2) identify patterns, and/or (3) compare different sets. Univariate statistics are often employed as part of an exploratory analysis, even when the problem at hand involves multiple variables.

DOI: 10.1016/B978-1-85617-797-9.00015-0

Descriptive Statistics

Due to time and cost constraints, a typical environmental data set consists of only a small sample of potential values that an investigated variable can acquire—that is, a small sample of the *population*. In the absence of the full knowledge of the investigated population, summary parameters are derived based on available samples. These parameters are referred to as descriptive statistics, which refer to a large class of parameters; however, this chapter will focus on three classes: measures of central tendency, measures of data dispersion, and standard error terms.

Measures of Central Tendency

Central tendency of data is normally measured by one of two methods: the sample mean or the sample median. The sample mean $\overline{X}$ is the most common measure of central tendency and is defined as

$$\overline{X} = \frac{\sum_{i=1}^{i=n} x_i}{n}$$

where x_i is the i^{th} measure value in the data set, and n is the number of measured values in the data set. As the value of n increases, the sample mean approaches the true, yet unknown, population mean.

The median value is the middle value of the data set ranked in order of magnitude. In the case where the number of samples in the data set is even, the sample median is the average of the two middle terms.

The sample mean is a good measure of the central tendency when the data set is symmetrically distributed. A common example of a symmetrical distribution is the so-called *normal* or *Gaussian* distribution. In the case of skewed data sets, the median may be a more appropriate measure of central tendency (Helsel and Hirsch, 1995).

Measures of Data Dispersion

The dispersion of a data set measures the spread of the sample around its mean value. Common methods of measuring dispersion calculate the variance and the standard deviation of a given data set. The sample variance, S^2, is defined as

$$S^2 = \frac{\sum_{i=1}^{n} (x_i - \overline{X})^2}{n-1}$$

and the sample standard deviation, S, is defined as

$$S = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \overline{X})^2}{n-1}}.$$

Standard Error Terms

Descriptive statistics discussed heretofore are *estimates* of specific population parameters. Such estimates, especially those based on small sample data sets, may sometimes produce unreliable results for decision making. To provide a level of confidence, error terms have been developed to quantify the uncertainty in descriptive statistics. The most common is the standard error of the mean, which provides an estimate of the error or uncertainty in estimating the mean of a sample. It does not provide any information on the error involved in measuring the data that make up the sample. The standard error of the mean (SE) is defined mathematically as

$$SE = \frac{S}{\sqrt{n}}$$

where

S = the sample standard deviation
n = the sample size

As the sample size increases, the uncertainty in the sample mean, or the standard error, decreases.

Confidence Limits

While data set characteristics may be summarized by descriptive statistics, questions commonly arise—for example: How confident are we in these estimated values? Can these statistics be represented as a range instead of a unique value? The calculation of confidence limits can provide answers to these questions. In this chapter, we focus on calculating the confidence limits around mean values and upper limits of our data set.

Confidence limits define the interval range within which a statistic can fall at a specific probability. Mathematically, the probability that a statistic X will fall within a given range is defined as

$$\Pr\{X_L \leq X \leq X_U\} = 1 - \alpha$$

where

X_L = the lower limit of the statistic
X_U = the upper limit of the statistic
α = the level of significance
$100(1 - \alpha)$ = the level of confidence

To calculate confidence limits for a statistic such as the mean, the underlying distribution of the data set must be known. If the data set is normally distributed, or large enough for a normal distribution to be assumed, the confidence limit of the mean is calculated as

$$\bar{X} \pm \frac{t_{(\alpha/2,n-1)}S}{\sqrt{n}}$$

or

$$\bar{X} \pm t_{(\alpha/2,n-1)}SE$$

where $z_{\alpha/2}$ is the standard normal variate with a cumulative probability of $100(1-\alpha/2)$ percent. In cases of small data sets $(n < 100)$, $z_{\alpha/2}$ can be substituted by $t_{(\alpha/2,n-1)}$, which is the Student's t variate with a cumulative probability of $100(1-\alpha/2)$ percent and $n-1$ degrees of freedom.

If normality of the mean cannot be assumed, which is often the case for small and highly skewed data sets, other methods including Chebyshev's and Boot Strap simulation techniques can be used to determine the confidence interval. For a detailed description of these methods, the reader is referred to "Calculating the Upper Confidence Limits for Exposure Point Concentrations at Hazardous Waste Sites" (USEPA, 2002).

Population Comparisons

Many environmental assessments involve procedures to determine whether two samples are drawn from the same population. Various statistical methods can be used to answer this question; however, as in most statistical analysis, the underlying population distribution is an important factor in the choice of method. Two methods are discussed: the Student's *t*-test and the Mann-Whitney test.

Student's t-Test

The *t*-test is a parametric method for testing the null hypothesis that data in two independent samples are taken from the same population against the alternative hypothesis that they are from different populations. A parametric variable can be described by a known probability distribution, and its parameters can be determined based on that distribution. The *t*-test assumes that the two samples are approximately normally distributed, are independent of each other, and have approximately equal variances. It works by comparing the means of the samples and determining whether they are significantly different.

Mathematically, the test statistic for the *t*-test is given as:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\frac{S_1}{\sqrt{n_1}} + \frac{S_2}{\sqrt{n_2}}}.$$

where

$\bar{X}_i$ = the mean of the i^{th} data set
S_i = the standard deviation of the i^{th} data set
n_i = the sample size of the i^{th} data set

If the variances are approximately equal, as assumed, then the test statistic can be defined in terms of the pooled variance:

$$t = \frac{\overline{X}_1 - \overline{X}_2}{s_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}.$$

where the pooled variance s_p is defined as:

$$s_p = \sqrt{\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}}.$$

The calculated t statistic is compared to tabulated t values at $n_1 + n_2 - 2$ degrees of freedom at the selected confidence level, referred to as the critical t value. If the calculated t statistic is greater than the critical t value, then the null hypothesis is rejected at that confidence level.

Mann-Whitney Test

The Mann-Whitney test, also known as the Wilcox rank sum test, is a nonparametric procedure used to test whether the measured values in two data sets are taken from the same population. The Mann-Whitney relies on ranked values and in effect compares the medians of the two data sets. Unlike the Student's *t*-test, the Mann-Whitney test makes no assumptions regarding the underlying population of the data set. It works by combining the two samples, ranking all the values from low to high (if multiple observations have the same rank, they are assigned the average of the ranks that would otherwise have been applied to the data), and comparing the samples' mean rank. The Mann-Whitney test is based on the U statistic, which is calculated as

$$U = n_1 n_2 + \frac{n_1(n_1 + 1)}{2} - R_1$$

where

n_1 = the number of observations in sample 1
n_2 = number of observations in sample 2
R_1 = the sum of the ranks occupied by observation in sample 1

The mean and variance of U is defined as

$$\overline{U} = \frac{n_1 n_2}{2}$$

$$S_U^2 = \frac{n_1 n_2(n_1 + n_2 + 1)}{2}.$$

If the calculated U value is greater than the tabulated critical U value for a particular significance level, the null hypothesis is rejected.

If n_1 and n_2 are large, the distribution of the U statistic approximates a normal distribution and the test can be based on the Z statistic as defined by

$$Z = \frac{U - \overline{U}}{S_U}.$$

The Z statistic is then compared to tabulated z values for the normal distribution. If the calculated value of Z falls within the range of z values for a two-tailed test, the null hypothesis cannot be rejected.

15.2.2 Multivariate Statistics

Multivariate statistics is used for analysis of patterns and trends of more than one variable at a time. It includes bivariate methods such as correlation analysis and more complex methods such as principal component analysis.

Correlation Analysis

Many environmental investigations involve analysis of patterns exhibited by paired measurements of two variables—for example, whether they are increasing or decreasing at the same time, whether one is increasing while the other is decreasing, or whether their variations show no relationship. Such patterns are first investigated through simple inspection of scatter plots of the investigated values. If visual evidence indicates the likelihood of some sort of a relationship between investigated variables, statistical methods can be used as confirmation. Commonly, two methods are used to evaluate such bivariate relationships: the parametric regression approach using Pearson's r coefficient, and the nonparametric procedure using Kendall's τ.

Pearson's *r* Coefficient

This approach is a parametric regression procedure used to quantify the degree of linear correlation between two variables x and y. It assumes that the underlying population for both the x and the y variables is normal. Mathematically, r is calculated as

$$r = \frac{\sum_{i=1}^{n}(x_i - \overline{X})(y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{X})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{Y})^2}}$$

where, x_i and y_i are the i^{th} values of x and y, and $\overline{X}$ and $\overline{Y}$ are the sample mean values. The value of r quantifies the strength of linear trend, which ranges from −1 to +1, with −1 representing a perfectly decreasing trend and +1 representing a perfectly increasing trend.

Irrespective of the magnitude of r, a test of significance must be performed to determine whether r is significantly different from 0. The significance of r is established by calculating a t statistic and comparing it to tabulated values of a t distribution at $n - 2$ degrees of freedom. The t statistic is calculated as

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}}.$$

Mann-Kendall Test

This test is a nonparametric procedure that determines the absence or presence of correlations in an ordered paired data set. It makes no assumption as to the underlying distribution of the data set and can identify both linear and nonlinear correlations. For this purpose, the Mann-Kendall test measures the probability that the two variables in the data set are in the same order against the probability that they are in different orders. The nonparametric measure of correlation is referred to as Kendall's τ, which is calculated over all possible pairs of data points as

$$\tau = \frac{concordant - discordant}{total\ pairs}$$

where

concordant = the number of pairs with the same relative time ordering of x
discordant = the number of pairs with opposite time ordering

The value of τ varies from −1 to +1, with −1 representing a perfectly decreasing trend and +1 representing a perfectly increasing trend.

Simple Linear Regression Analysis

The technique of simple linear regression is used to establish a linear relationship that shows the dependency of one variable on the other. It is used to develop a predictive model for the dependent variable based on the independent variable. However, the analyst must be cognizant of the fact that simple linear regression and its advanced versions are statistical procedures that are not intended to be used for cause-and-effect determination. Any such conclusion should be supported solely based on nonstatistical physical, chemical, or biological observations.

The linear regression model is defined as

$$y_i = a_0 + a_1 x_i + \varepsilon_i$$

where

i = 1 to n
n = the number of samples
y_i = the i^{th} observation of the dependent variable

x_i = the i^{th} observation of the independent variable
a_0 = the intercept
a_1 = the slope of the regression line
ε_i = the error term

The estimates of a_0 and a_1 are based on the method of ordinary least squares using the following equations:

$$a_0 = \overline{Y} - a_1\overline{X}$$

$$a_1 = \frac{\sum(x_i - \overline{X})(y_i - \overline{Y})}{\sum(x_i - \overline{X})^2}.$$

The amount of variability in the dependent variable explained by the regression model is defined by the coefficient of determination r^2, calculated as

$$r^2 = a_1^2 \frac{\sum_{i=1}^{n} x_i^2 - n\overline{X}^2}{\sum_{i=1}^{n} y_i^2 - n\overline{Y}^2}.$$

Multiple Regression Analysis

It is sometimes necessary to develop linear predictive models that involve more than one independent variable. This can be achieved by an expansion of the linear regression model using its additive property. The resulting multiple linear regression model used for k independent variables is referred to as a multiple regression model and is defined as

$$y_i = a_0 + a_1x_{1i} + a_2x_{2i} + \ \ldots\ldots + a_kx_{ki} + \varepsilon_i$$

where

i = 1 to n
k = 1 to j
n = the number of paired samples
j = the number of independent variables
y_i = the i^{th} observation of the dependent variable
x_{ki} = the i^{th} observation of the k^{th} independent variable
a_0 = the y intercept
a_k = the slope of the regression line corresponding to the k^{th} variable
ε_i = the error term

The parameters of the multiple regression equation are best calculated by matrix algebra. In matrix form, the multiple regression equation is given as

$$Y = XA + E$$

or

$$\begin{pmatrix} y_1 \\ y_2 \\ . \\ . \\ y_n \end{pmatrix} = \begin{bmatrix} 1 & x_{11} & x_{12} & . & . & x_{1k} \\ 1 & x_{21} & x_{22} & . & . & x_{2k} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ 1 & x_{n1} & x_{n2} & . & . & x_{nk} \end{bmatrix} \begin{pmatrix} a_0 \\ a_1 \\ . \\ . \\ a_k \end{pmatrix} + \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ . \\ . \\ \varepsilon_n \end{pmatrix}$$

where,

y_i = the i^{th} observation of the dependent variable
x_{ij} = the i^{th} observation of the j^{th} independent variable
a_o = the y intercept
a_j = the coefficient of the regression line corresponding to the j^{th} variable
ε_i = the error term associated with the i^{th} observation

Assuming that $X'X$ has an inverse, the unique solution to the multiple regression matrix is given by:

$$\hat{A} = (X'X)^{-1}(X'Y)$$

where X' is the transpose of matrix X.

Multiple regression procedure is based on a number of underlying assumptions, including the statistical independence of independent variables. If these variables proved to be correlated, the resulting estimated regression coefficients cannot be viewed as reliable or meaningful values. This condition is known as *multi-co-linearity*, which is especially problematic when environmental decisions are supposed to be made based on magnitudes of the estimated regression coefficients.

Principal Component Analysis

Many environmental decisions involve a multitude of variables. Simultaneous analysis of large numbers of variables poses many computational challenges. One option is to reduce the dimensionality of the data set. The objective of Principal Component Analysis, or PCA, is to exploit correlations among investigated variables in order to transform the multivariate (multidimensional) data set into a simpler data set consisting of fewer, uncorrelated variables—known as *principal components*. This transformation is accomplished based on the correlations exhibited by the investigated variables. The stronger the correlations among the variables, the fewer principal components are necessary to explain the variability of the investigated data.

Each principal component is a linear combination of the investigated variables. The coefficients in these linear combinations are referred to as the *loadings*. In mathematical terms, the loadings associated with each principal component constitute an eigenvector of the correlation matrix, and the portion of the variability that is explained by this component is proportional to its corresponding eigenvalue. The principal components are ranked as first to last according to the magnitude of their eigenvalues. So the principal component that explains most of the variability of the data set (i.e., corresponding to the highest eigenvalue) is referred to as the first principal component (DON, 2009).

When the investigated variables are correlated, the first two or three principal components account for a large percentage of the variability of the data set. In such cases, each sample is identified by the values of its first few principal components—that is, its *principal component scores*. So instead of a simultaneous analysis of many variables in a multitude of samples, the relationship between samples can be assessed by simple inspection of a two- or three-dimensional plot, also referred to as the principal components scores plot. For a thorough discussion of PCA, the reader is referred to Johnson and colleagues (2002).

15.2.3 Spatial Statistics/Geostatistics

Geostatistics is widely used in the analysis of correlated spatial data in various fields of natural resources management including environmental science, hydrology, and mining. Classical (nonspatial) statistical methods assume that the investigated data are unbiased, unclustered, and independent—in other words, devoid of any correlations. In practice, however, field data, such as groundwater or soil samples, are collected in a biased fashion, are clustered around critical locations, and are expected to display a degree of spatial structure. Geostatistics recognizes these properties and, according to well-defined criteria, provides the statistical tools for determining spatial correlations, calculating estimations between data points, and quantifying the accuracy of such estimations.

Quantitative determination of spatial correlation among investigated data is accomplished through the *variogram analysis*. This analysis is initiated by computation of sample variograms. For this purpose, all pairs of measurement values in a data set are compared to each other in order to provide a consistent measure of their degree of spatial correlation. The resulting differences between paired measurements are then grouped according to their separation distance and the orientation of their separation vector. For each specific orientation (direction), the grouped differences are plotted with respect to their separation distances, yielding a sample variogram plot. This plot allows the user to quantify and model the spatial correlation along targeted directions.

Mathematically, the variogram is defined as:

$$\gamma_{ij} = \frac{1}{2} E[Z_i - Z_j]^2$$

where,

γ_{ij} = (semi-) variogram between Z_i and Z_j
Z_i = data value at the i^{th} time
E = the expected value operator

Each data set has its own sample variogram characteristics. The variogram of a data set exhibiting correlation is qualitatively and quantitatively different from the variogram of a data set that is random. For data that display a well-defined correlation, the variogram plot can be used to measure the spatial extent of related data (i.e., its "range"). Examples of different types of variograms are described in the following and graphically presented in Figure 15.1.

Structured. A variogram plot such as the spherical plot that indicates that the nearby data points in the data set are related to each other. That is, they exhibit a pattern. The spatial extent of the pattern can be calculated based on the size of

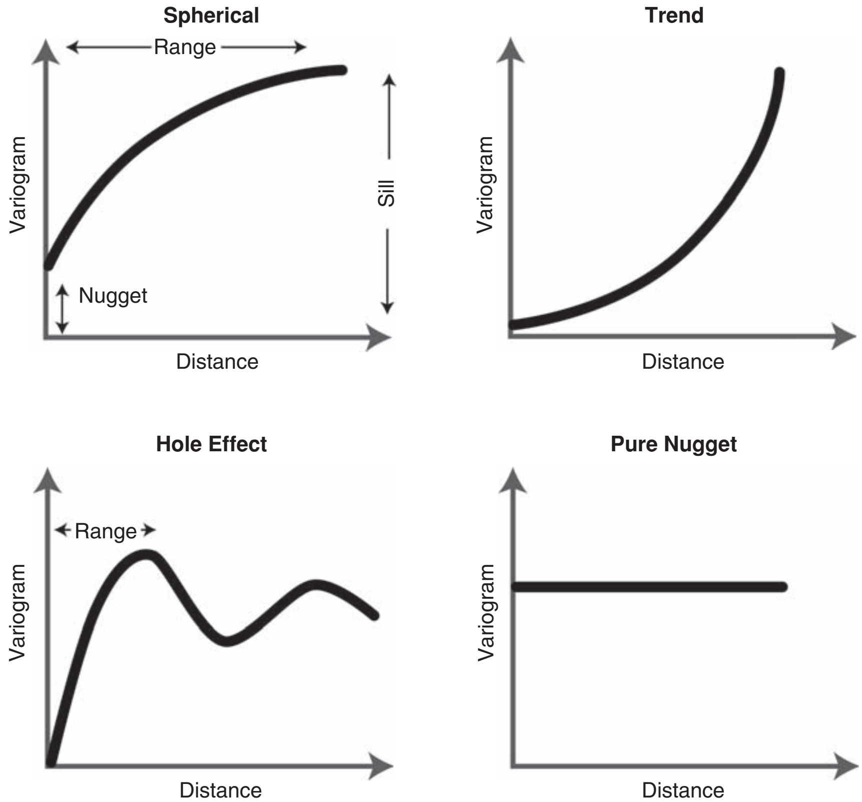

FIGURE 15.1

Samples of variogram types.

the range, as shown in Figure 15.1. Other components of the variogram include the sill (the statistical variance of the investigated variable) and the nugget (the variance due to measurement errors and/or micro-scale variations).

Trend. A variogram plot that indicates that the measured values are gradually increasing from one zone to another.

Hole-effect. A variogram plot that indicates that the related data are clustered in isolated pockets. The size of these isolated pockets can be calculated based on the range.

Pure-nugget. A variogram plot that indicates that the data are devoid of any spatial structure (i.e., completely random).

Upon determination of the variogram model, the geostatistical estimation process can be performed either by point or block kriging. As the names imply, point kriging estimates on a point-by-point basis, whereas block kriging yields average values over defined spatial units. Mathematically, point or block kriging can be represented by the following equation:

$$Z_0^* = \sum_{i=1}^{n} \lambda_i z_j$$

where

Z_0^* = the estimated point or block value centered at x_0
z_{i} = the measured value at x_i
λ_i = the estimation weight of z_i

The computations of these estimation weights are based on two criteria: nonbias condition and minimum estimation variance. In statistical terms, geostatistical estimates are the best linear unbiased estimates. Any point or block estimate Z_0^* comes with its own measure of accuracy in the form of an estimation (kriging) standard deviation, usually denoted σ_0.

15.2.4 Monte Carlo Simulations

Statistical and geostatistical techniques are generally suitable for the analysis of most environmental data sets. However, in some instances the complexity of the problem does not lend itself to an analytical or closed-form solution. Under such instances, repetitive simulations of the problem can provide a large basis for conducting specific inference tasks. This can be achieved by the technique of Monte Carlo simulations. The technique is based on random sampling to create multiple data sets or realizations of the variable of interest.

In its simplest form, a univariate system can be modeled as:

$$y = f(x)$$

where y is the output, which is defined as a function of the input variable x.

The range of values of the input variable x are generally known and defined as a probability density. The Monte Carlo simulation is then performed by randomly drawing a value of x from its probability distribution and calculating the value of y. This process is repeated many times (1000+) to create a simulated distribution of y values. The simulated distribution of y values can then be analyzed statistically for a variety of purposes, including descriptive statistics and confidence intervals computations.

The same process can also be applied to multivariate system such as:

$$y = f(x_1, x_2, x_3, \ldots\ldots\ldots x_n)$$

where y is a function of multiple variables x_1 to x_n, all defined by their own specific probability and cross-probability density functions. The solution of this model will follow the method just described, but each step requires the repetitive random simulations of values for x_1 to x_n.

15.3 SUGGESTED READING

The statistical methods discussed in this chapter represent commonly used techniques in environmental applications. However, in many instances, specific site conditions or particular decisions demand the use of specialized methods. Examples of such applications can be found in the literature, including some discussed among the following suggested reading list. For a more detailed descriptions of these and other statistical methods, the reader is directed to the following:

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CHAPTER 16

Chemical Fingerprinting: Streamlining Site Assessment during the Sustainable Redevelopment Process

Allen D. Uhler, Scott A. Stout, Stephen D. Emsbo-Mattingly, Shahrokh Rouhani

16.1 INTRODUCTION

Petroleum hydrocarbons, manufactured gas plant wastes, creosote, and other industrial chemicals, such as PCBs and dioxins, are ubiquitous environmental contaminants. Their complex chemical composition makes determination of their true nature and origin difficult, and makes assignment of responsibility for and ownership of contamination problematic. Sites found contaminated with such chemicals during traditional phase I or phase II site assessments ultimately require that the origins of and responsibility for such contamination be identified and equitably remediated by responsible parties.

Often, the complex nature of site contamination, its sources, and the fair allocation of response costs can dramatically slow remediation efforts and ultimately thwart site redevelopment. Solutions to these near intractable remediation allocation problems have created a need for assessment tools that offer a technically sound, defensible means to determine the nature, sources, and age of site contamination and to unravel the likely responsibility for remedial efforts.

In the last decade, the need for assessment tools has led to the development of environmental forensics: the systematic investigation of a contaminated site or an event that has impacted the environment (Morrison, 2000). The cornerstone of virtually all environmental forensic investigations is advanced chemical measurements. These are sufficiently detailed to generally provide data that identify the nature of contamination and differentiate among sources of similar contaminants. They are often referred to as "chemical fingerprinting" (Stout et al., 1998).

Armed with chemical fingerprinting data, and drawing on available historic (both operational and regulatory) geologic, hydrologic, or meteorological data, a site investigator is in a strong position to determine the origin(s) or source(s) of the contamination and to distinguish true site contaminants from naturally occurring or anthropogenic background chemicals. In some instances, this same

DOI: 10.1016/B978-1-85617-797-9.00016-2

information may be helpful in constraining the most likely duration of time that has passed since the contaminants were released into the environment.

16.2 CHEMICAL FINGERPRINTING

With few exceptions, the data requirements for a chemical fingerprinting investigation differ from data requirements of studies driven by regulations. In regulatory assessments such as those carried out under the auspices of the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) and the Resource Conservation and Recovery Act of 1976 (RCRA), only a limited number of parameters and chemicals of concern are measured to determine the nature and extent of contamination (Uhler et al., 1998–1999). Examples of such measurements include the following:

- Total petroleum hydrocarbons (TPH), concentrations of water-soluble benzene, toluene, ethyl-benzene, and *o*-, *m*-, and *p*-xylenes (BTEX) using EPA Method 8260B
- The 16 Priority Pollutant polycyclic aromatic hydrocarbons (PAHs) by EPA Method 8270C
- Total Aroclors by EPA Method 8082

Compliance-driven measurements, although adequate for gross descriptions of the extent and types of contaminants found at a site, are largely insufficient to address the issue fundamental to an environmental forensic investigation: obtaining a detailed understanding of the chemical nature, source, and age of site contamination. Defensible results require developing the appropriate chemical fingerprinting data, beyond that typically obtained with standard regulatory chemical analyses, using appropriate and technically accepted methodologies (Wait, 2000).

To obtain this type of data, environmental forensic chemists have expanded or otherwise modified basic EPA methods of analysis, or have developed new methods to more thoroughly characterize the nature of contamination. Most of these modified or new methods have been published in the peer-reviewed scientific literature or in authoritative books or promulgated treatises (e.g., in the U.S. Federal Register).

Chromatography techniques lie at the heart of most chemical fingerprinting methods used in the characterization of hydrocarbons, PCBs, dioxins, and other organic contaminants. The heavy reliance on this technique is a function of its extraordinary ability to separate complex mixtures of organic compounds and measure individual chemicals using a wide range of specialized detectors. It must be remembered that petroleum- and coal-derived materials contain thousands of compounds that range in concentration over several orders of magnitude. Similarly, PCB Aroclors and chlorinated dioxins and furans are complex mixtures of over 100 individual compounds. Specialized high-resolution chromatography methods are required to measure hydrocarbon and PCB constituents with demonstrable accuracy and precision.

Measurements of complex mixtures of chemicals such as hydrocarbons, PCBs, and dioxins follow standardized Environmental Protection Agency (EPA) methods of analysis (e.g., EPA, 1994; EPA, 1997; EPA, 1999). Modifications of standard methods, however, provide significantly more detailed chemical composition information (Douglas and Uhler, 1993). The technical challenges faced by environmental forensic investigators using standard EPA methods include the absence of appropriate target analytes for forensic studies, relatively high detection limits, and requirements for the generic operation of gas/chromatographic (GC) instruments (Douglas and Uhler, 1993; Stout et al., 2002).

Fortunately, the EPA reference methods from SW-846 are classified as performance-based measurement systems (PBMS), which encourages their adaptation for optimal service to project objectives so long as established performance criteria are satisfied and demonstrated (EPA, 2001). Section 2.1 of SW-846 (EPA, 1997) states,

> *If an alternative analytical procedure is employed, then EPA expects the laboratory to demonstrate and document that the procedure is capable of providing appropriate performance for its intended application. This demonstration must not be performed after the fact.*

Strictly for business purposes, most commercial laboratories are not interested in modifying standard "production line" chemistry methods. In contrast, the necessity of measuring different suites of target analytes at low detection limits requires forensic laboratories to alter standard methods to meet project goals with the understanding that standard method guidelines will be observed to the maximum extent practicable. This means that modified EPA methods can be used to support both chemical fingerprinting investigations and regulatory monitoring.

Qualitative and quantitative features of GC analyses are equally important in chemical fingerprinting. For example, Figure 16.1 depicts GC traces of a representative crude oil and several petroleum products. The distinctive differences visually observed in these gas chromatograms reflect the products' unique chemical composition. It is these qualitative features that chemists use to identify the nature of hydrocarbon contamination in environmental samples.

Quantitative measurements of individual chemicals from chromatography analyses are used to develop a more detailed understanding of the chemical makeup of complex contaminant mixtures. Consider Figure 16.2, which depicts a forensic-quality gas chromatogram of an automotive gasoline measured by gas chromatography with mass spectrometry (GC/MS); the quantitative measurements of almost 100 individual chemicals that make up the gasoline are depicted in the bar chart below the GC trace.

The occurrence and relative amounts of the gasoline's constituents can be used by forensic chemists to describe its exact makeup. They can also be used to link or differentiate that gasoline from other environmental samples or suspect gasoline sources by comparing its chemical makeup with that of samples taken in the

WIDE MOLECULAR WEIGHT RANGE

Crude Oil

Crude oil is the primary feedstock for a petroleum refinery. This complex hydrocarbon mixture is the source of many petroleum-derived materials.

MIDDLE DISTILLATE RANGE

#2 Fuel Oil

After distilling light hydrocarbons for gasoline, middle distillates, like this #2 fuel oil, are distilled from the crude oil feedstock.

INTERMEDIATE RANGE

#4 Fuel Oil

Intermediate fuel oils are commonly blended to include middle distillates and heavy fuel oils.

RESIDUAL RANGE

#6 Fuel Oil

Heavy fuel oils fall into the residual range of crude oil. They may be composed of heavy distillates that are generated after middle distillates are removed.

REFINED HEAVY DISTILLATE

Heavy Distillate

Heavy distillates are refinery stocks that can be further processed for myriad industrial applications.

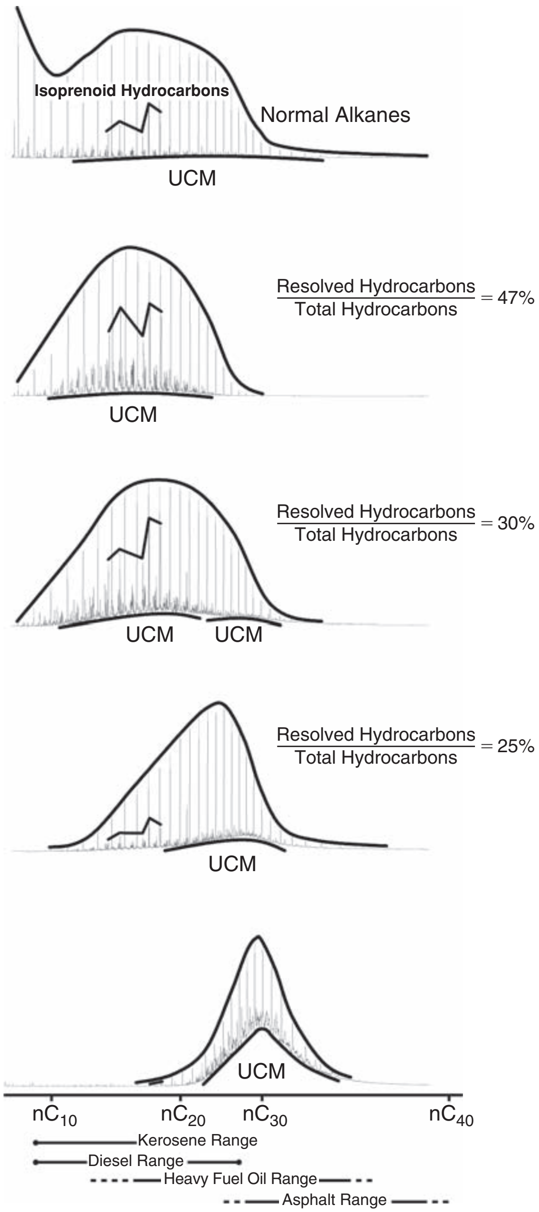

FIGURE 16.1

Examples of qualitative gas chromatography "fingerprints" of selected petroleum products.

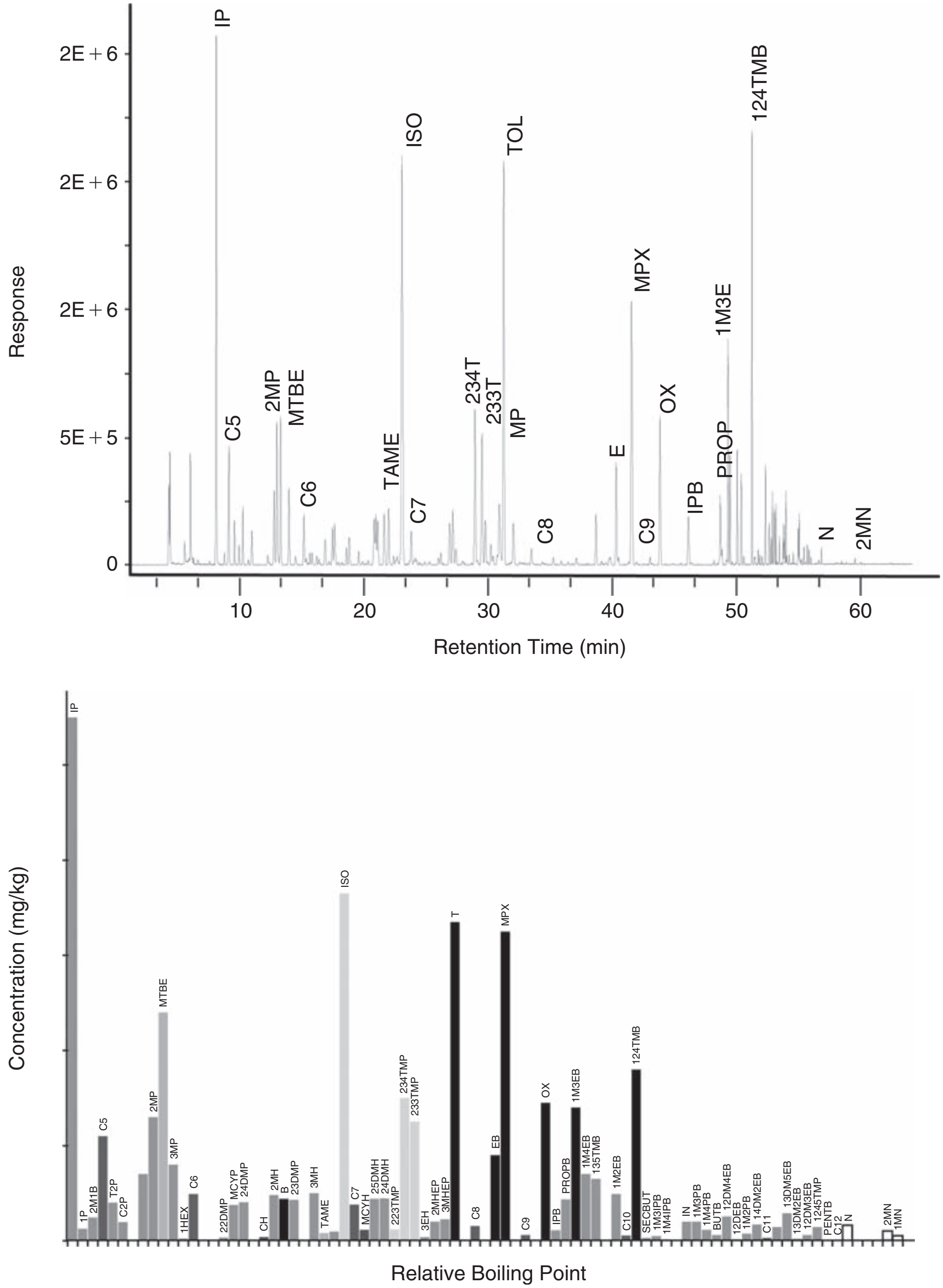

FIGURE 16.2

Gas chromatography fingerprint of a premium gasoline (*top*) and the quantitative compound concentration bar chart derived from its analysis (*bottom*).

field. In contrast, the standard regulatory method used to characterize gasoline-range contamination (EPA Method 8260 *Volatile Organic Compounds By Gas Chromatography/Mass Spectrometry* (GC/MS)) measures only 6 of the more than 100 important chemicals found in gasoline, whose concentrations and relative distributions form the basis for quantitative chemical fingerprinting of automotive fuel (Uhler et al., 2003).

16.3 ADAPTATION OF EXISTING METHODS TO CHEMICAL FINGERPRINTING

Chemists have invested many years in the development of chemical fingerprinting methods and in the adaptation of standard EPA methods to yield the necessary data to support detailed forensic investigations. The first technical challenge in this effort is generating an appropriate target analyte list. For example, the appropriate target analytes for the analysis of petroleum, coal, and PCB Aroclors include numerous compounds that are not listed in EPA standard methods.

That said, the analytes used in forensic investigations (e.g., hydrocarbons and PCB congeners) behave very similarly to many of the regulated compounds listed in the EPA reference methods. Therefore, adapting standard EPA reference methods to the measurement of extended lists of target compounds is appropriate.

The second technical challenge is modifying existing methods so they provide adequate sensitivity and detection limits. This ability to detect low concentrations of target analytes is often important when measuring materials composed of complex mixtures, where the analytes may range in concentration over several orders of magnitude. Essentially, standard methods are tailored for fingerprinting by optimizing sample preparation, cleanup, and instrumentation measurement steps.

The third technical challenge is to develop routine procedures for ensuring the generation of high-quality data over time. Methods for measuring forensic analytes must be associated with an active system for monitoring and demonstrating that the target analytes are measured with acceptable accuracy and precision.

Collectively, the measurement of appropriate analytes using optimized procedures under an established quality control and assurance program satisfies the PBMS guidelines for determining the acceptability of chemical fingerprinting methods (EPA, 2001).

16.4 APPLICATIONS OF CHEMICAL FINGERPRINTING

High-quality chemical fingerprinting data from samples containing petroleum, tars, PCBs, dioxins, and other man-made industrial chemicals provide significant information about the chemical makeup of the contamination. When forensic-quality chemical measurements are carried out on environmental samples, distinctive features of site- or source-specific contamination are usually revealed.

These distinctive chemical features are used by forensic chemists to "fingerprint" the contamination.

The resulting chemical fingerprints are used in various ways—for example, to ascertain if a certain industrial source is responsible for a discovered off-site contamination or to distinguish contribution from multiple sources of similar (but distinguishable) contaminants. Following are examples of chemical fingerprinting in environmental forensic investigations.

16.4.1 Assessing the Impact of a Crude Oil Spill Following Hurricane Katrina

Murphy Oil Corporation owns and operates the 100,000-barrel per day Meraux Refinery in St. Bernard Parish, Louisiana. During the flooding that occurred during landfall of Hurricane Katrina on August 29, 2005, a 250,000-barrel above-ground storage tank was dislodged and then ruptured. A crude oil feedstock stored in the tank at the time, consisting primarily of a Nigerian Bonnie Light crude, was released into the receding floodwaters. Some of it flowed with the floodwaters into the adjacent community of Meraux. Assessing the extent of the spill's impact was an important component in the management of the cleanup settlement for residents and in the management of a class action lawsuit filed against Murphy Oil Corporation.

As part of the after-spill assessment, chemical fingerprinting was conducted on over 15,000 samples collected from over 5,000 homes, businesses, churches, and schools to establish the presence or absence of Murphy Oil's crude oil on each property (Stout et al., 2006). A two-tier strategy was developed that included both a qualitative (tier 1) and quantitative (tier 2) assessment.

The heart of the program was the tier-1 qualitative gas chromatography assessment of the hydrocarbons found on affected properties or structures, which followed existing ASTM oil spill fingerprinting protocols (ASTM D3328 and D5739). Its purpose was to determine whether hydrocarbon signatures found in environmental samples met qualitative criteria as potential "matches" with the spilled oil.

Selected tier-1 samples were further assessed using quantitative oil spill fingerprinting techniques (tier 2) to calibrate the qualitative model. The samples that contained the spilled oil (Figure 16.3) could be differentiated from those that contained other nonspill hydrocarbons (such as plant waxes from peat) and from distillate fuels or lubricating oils that were released into the environment from other sources during the flooding. This methodology was used to map locations within the Meraux study area that were impacted by the spilled oil (Figure 16.4).

Most of the positive matches occurred within an acknowledged area of impact. Many negative matches were dispersed among the positive matches. This heterogeneous distribution of impact demonstrated the existence of disparate impact within the spill area. The heterogeneity in the distribution of impacted soils/ sediments and wipes from structures, in turn, demonstrated that the crude oil

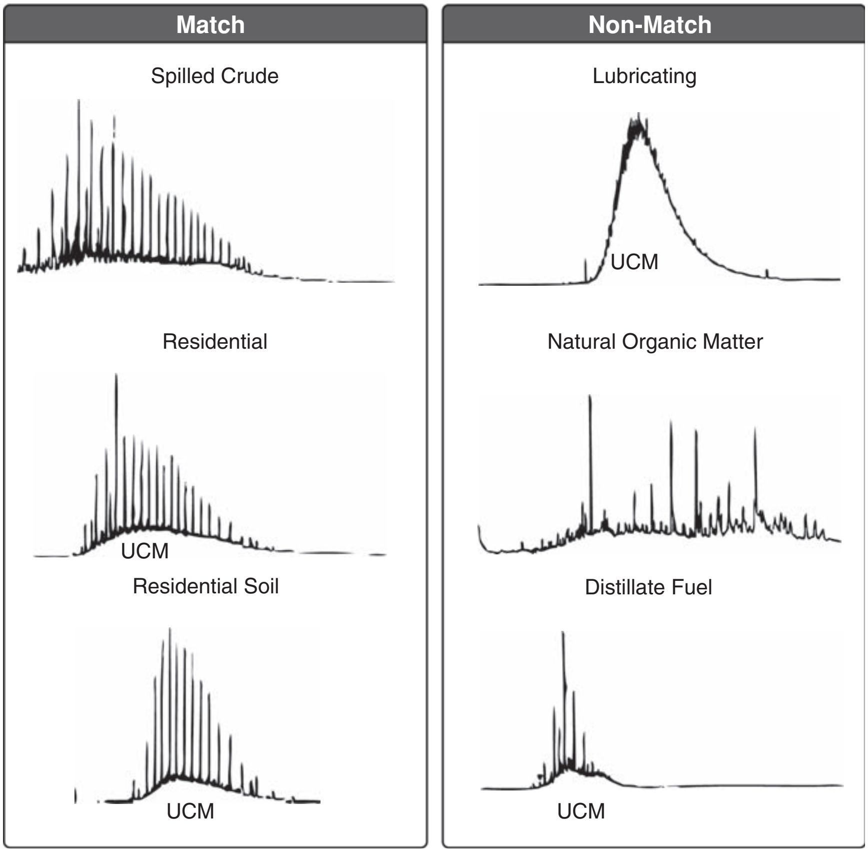

FIGURE 16.3

Examples of “positive match” and “negative match” gas chromatographic fingerprints between spilled crude oil and environmental samples. *Source*: From Stout et al., 2006.

slick was discontinuous and that many factors affected whether or not the oil “settled” on outside soils or inside sediments or adhered to structures. Among these factors were likely to be wind conditions, the influence of storm drains and canals on water drainage, the fragmenting effect of obstructions on the floating slick(s), and the local topography.

The results of the fingerprinting assessment were used to scientifically classify the spilled oil’s area of impact. This classification system was used to define the class boundary in *P. Turner et al. v Murphy Oil USA, Inc. et al.* (U.S. District Court, C.A. No. 05-4144)—which was significantly reduced from the Plaintiff’s original claim—and to guide Murphy’s settlement program with affected property owners within the class.

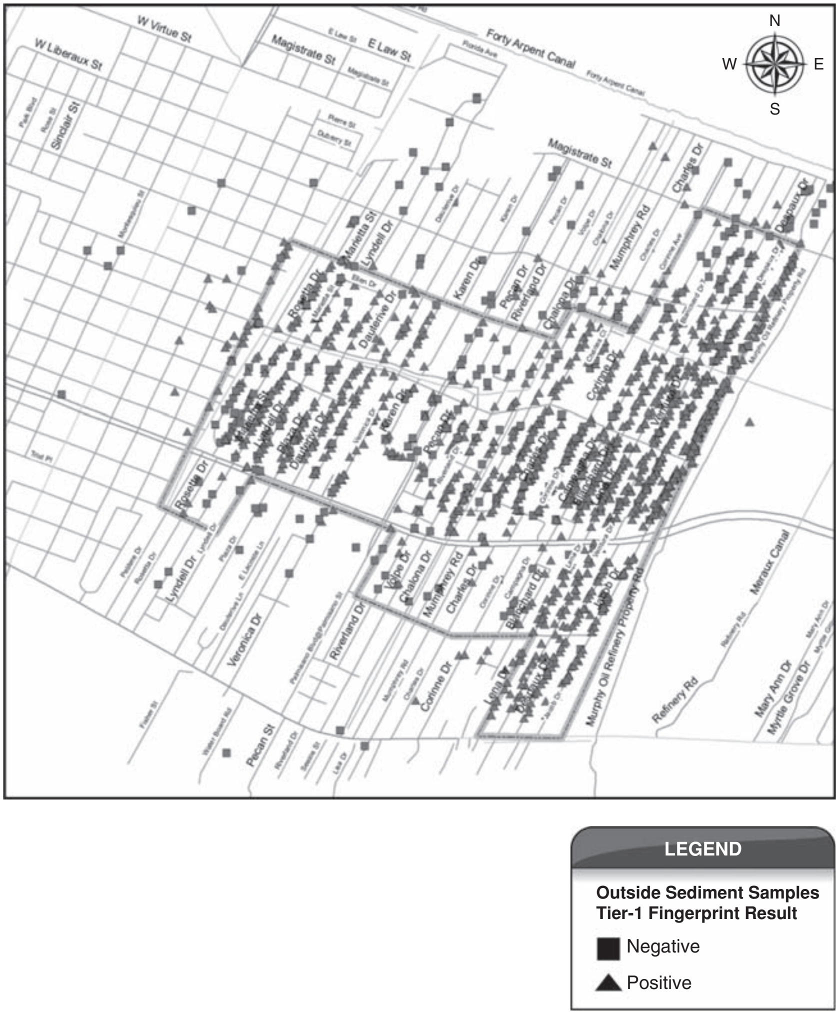

FIGURE 16.4

Map showing distribution of positive and negative tier-1 fingerprinting matches for soils/sediments and wipes collected near Meraux, Louisiana.

16.4.2 Identifying Manufactured Gas Plant Tar Wastes in Sediments

Manufactured Gas Plants (MGPs) provided town illumination gas and were common in many parts of the United States from the mid-1800s through the mid-1900s. Environmental legacies at former MGP sites can include MGP-derived tar residues, which are complex mixtures of hydrocarbons formed from the pyrolysis of coal and/or oil. The composition of MGP tars is dominated by polycyclic aromatic hydrocarbons (PAHs). There are well-documented distinctions in the PAH chemical fingerprints of tars, petroleum, and other PAH sources, notably urban runoff (Stout et al., 2002). However, those distinctions can only be recognized using chemical fingerprinting techniques.

During redevelopment at a waterfront industrial site in Northern California that had most recently housed a petroleum bulk fuel storage facility, elevated concentrations of PAHs were discovered in proximal near-shore sediments. It was well documented that an oil-fired MGP plant had operated on an adjoining property for several decades near the turn of the century. Were the PAH found in the sediments near the site derived from modern refined petroleum releases, former MGP operations, or other point or nonpoint sources such as urban runoff?

An initial chemical fingerprinting assessment of the hydrocarbon contamination in the sediments was carried out using qualitative GC techniques followed by measurements of detailed PAH and selected diagnostic heteroatomic compound measurements using gas chromatography with mass spectrometry (GC/MS). The expanded list of PAH compounds measured using this technique (Figure 16.5) provided unique product- and source-specific compositional information (Douglas et al., 2007). The distinctive GC fingerprints and PAH distributions of MGP wastes (Emsbo-Mattingly et al., 2002), petroleum products (Stout et al., 2002), and general urban sediment contamination (Stout et al., 2004) are documented in the literature and can be used to identify the general nature of sediment contamination (Figure 16.6).

Through examination of the gas chromatography/flame ionization detection (GC/FID) fingerprints and the distributions of PAHs at the MGP site, the hydrocarbon contamination in the near-shore sediments was grouped into three categories:

Group 1. Relatively fresh MGP wastes
Group 2. Weathered MGP wastes
Group 3. MGP wastes mixed with naturally occurring plant hydrocarbons

Both the GC fingerprints and the PAH distributions revealed that the major PAH constituents in the sediments were naphthalene, phenanthrene, and the fluoranthene/pyrene doublet (Figure 16.7). These chemicals, their relative distribution, and the very low concentrations of their respective alkylated PAH homologues were consistent with classic MGP residues.

The PAH patterns were inconsistent with urban runoff, soot, and atmospheric debris, whose PAH distributions tend to be dominated by 4-ring through 6-ring PAHs, with significantly lesser amounts of 2-ring and 3-ring PAHs. The PAH patterns noted in the sediments were clearly different from refined or crude petroleum, whose PAH distributions are exemplified by “bell-shaped” distributions of the alkylated PAH homologues (see inset in Figure 16.7).

Supporting the thesis that the PAHs found in the sediments were consistent with oil-fired gas plant waste was analysis of the diagnostic PAH ratio of fluoranthene to pyrene (FL/PY). This particular ratio is known to be influenced by

Abbrv.	Target Compound
N0	Naphthalene
N1	C1-Naphthalenes
N2	C2-Naphthalenes
N3	C3-Naphthalenes
N4	C4-Naphthalenes
B	Biphenyl
DF	Dibenzofuran
AY	Acenaphthylene
AE	Acenaphthene
F0	Fluorene
F1	C1-Fluorenes
F2	C2-Fluorenes
F3	C3-Fluorenes
A0	Anthracene
P0	Phenanthrene
PA1	C1-Phenanthrenes/Anthracenes
PA2	C2-Phenanthrenes/Anthracenes
PA3	C3-Phenanthrenes/Anthracenes
PA4	C4-Phenanthrenes/Anthracenes
RET	Retene
DBT0	Dibenzothiophene
DBT1	C1-Dibenzothiophenes
DBT2	C2-Dibenzothiophenes
DBT3	C3-Dibenzothiophenes
DBT4	C4-Dibenzothiophenes
BF	Benzo(b)fluorene

Abbrv.	Target Compound
FL0	Fluoranthene
PY0	Pyrene
FP1	C1-Fluoranthenes/Pyrenes
FP2	C2-Fluoranthenes/Pyrenes
FP3	C3-Fluoranthenes/Pyrenes
FP4	C4-Fluoranthenes/Pyrenes
NBT0	Naphthobenzothiophenes
NBT1	C1-Naphthobenzothiophenes
NBT2	C2-Naphthobenzothiophenes
NBT3	C3-Naphthobenzothiophenes
NBT4	C4-Naphthobenzothiophenes
BA0	Benz[a]anthracene
C0	Chrysene/Triphenylene
BC1	C1-Chrysenes
BC2	C2-Chrysenes
BC3	C3-Chrysenes
BC4	C4-Chrysenes
BB	Benzo[b]fluoranthene
BJK	Benzo[k]fluoranthene
BB	Benzo[a]fluoranthene
BEP	Benzo[e]pyrene
BAP	Benzo[a]pyrene
PER	Perylene
IND	Indeno[1,2,3-cd]pyrene
DA	Dibenz[a,h]anthracene
GHI	Benzo[g,h,i]perylene

FIGURE 16.5

Diagnostic PAH and alkylated PAH measured in chemical fingerprinting investigations.

the temperature at which hydrocarbons are combusted. An FL/PY ratio greater than 1.0 indicates that a high-temperature combustion process is responsible for PAH production, while a ratio less than 1.0 is indicative of lower-temperature processes, including those encountered during oil gas generation. The average FL/PY ratios for the three sample groups identified in the first phase of this assessment ranged from 0.75 to 0.89—all consistently below 1.0.

The data supported the theory that a lower-temperature process, consistent with the carbureted water gas process used at the former MGP site, was responsible for the PAHs found in the local sediments. This finding largely eliminated significant input from urban runoff or atmospheric deposition as major sources

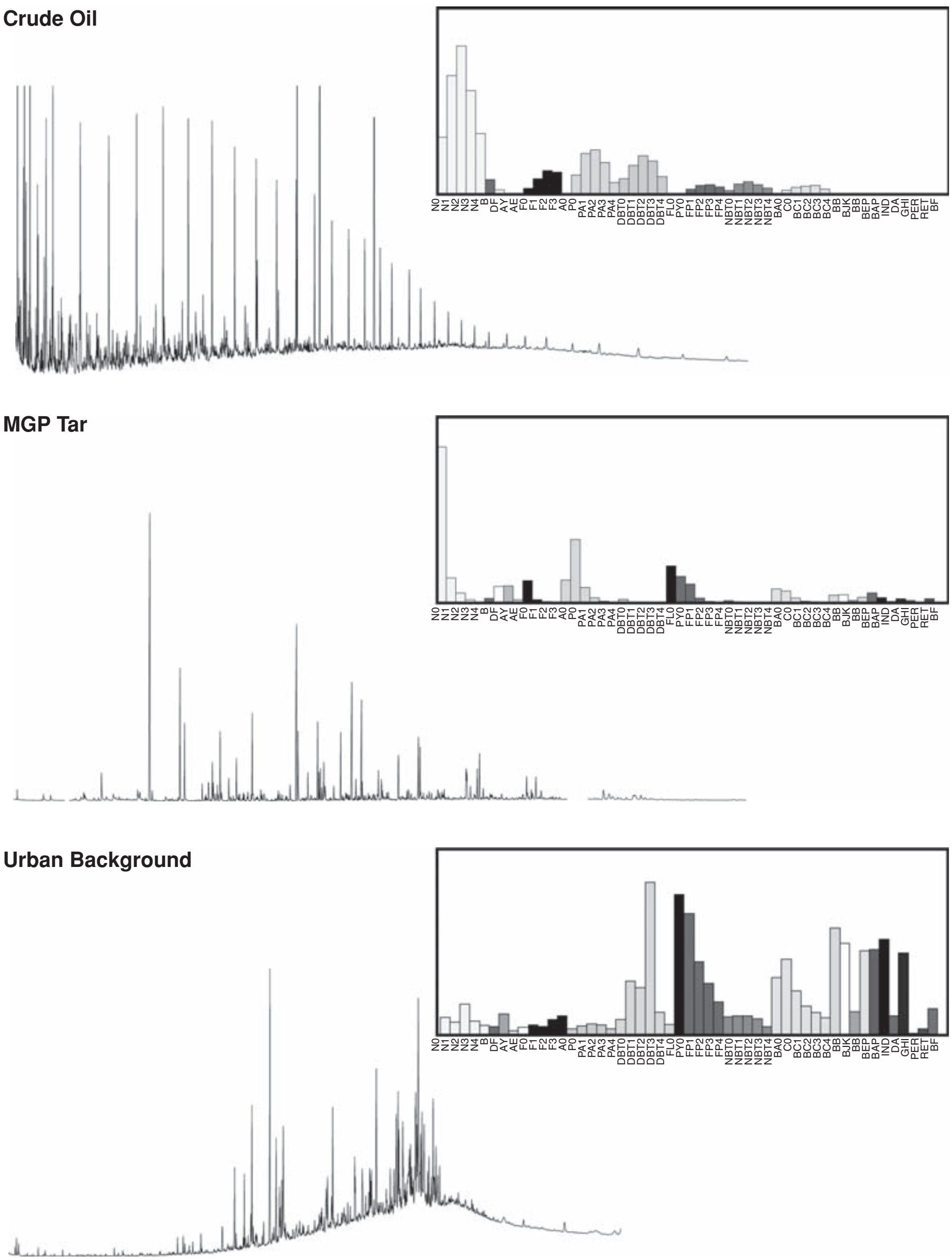

FIGURE 16.6

Gas chromatographic fingerprints and PAH patterns (insets) for crude oil, MGP tar, and urban background sediment.

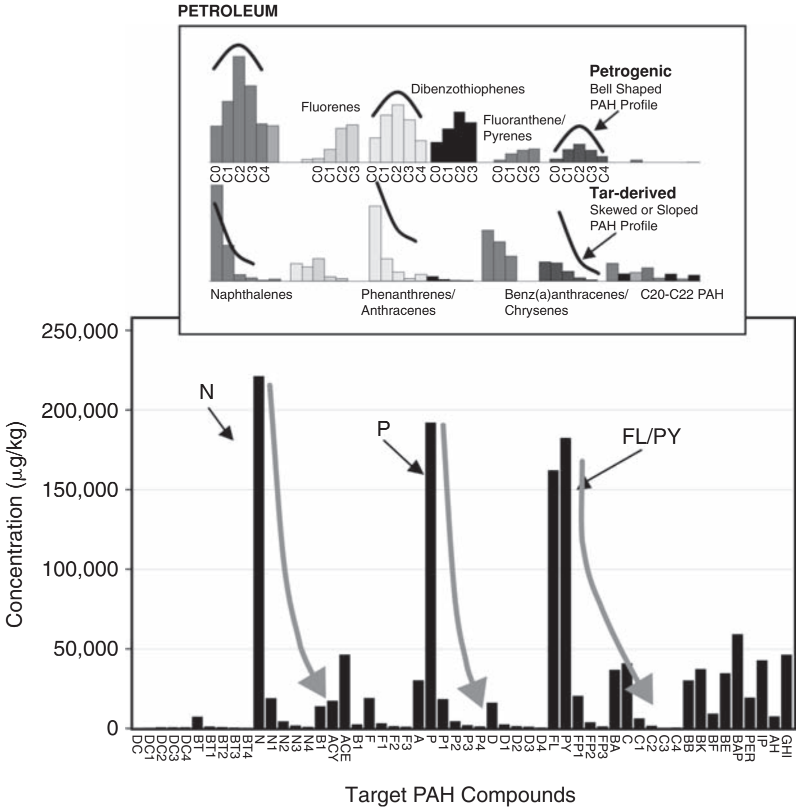

FIGURE 16.7

Distribution of PAH compounds measured in near-shore sediments.

of PAHs in the sediments in question, since PAHs from these sources are formed by a high-temperature process and yield PAHs that have FL/PY greater than 1.0.

Together, the qualitative gas chromatography data, quantitative PAH distribution data, and diagnostic PAH ratio data supported a conceptual model consistent with sediment PAH contamination arising from the former MGP site activities, not the petroleum bulk fuel storage facility operations.

16.4.3 Determining Dioxin and Furan Impacts from a Former Wood-Treating Facility

The Coleman-Evans Wood Preserving Superfund Site contains 11 acres located in the town of Whitehouse, Florida, approximately 10 miles west of downtown Jacksonville. From 1954 to the mid-1980s, Coleman-Evans treated wood products with a mixture of pentachlorophenol (PCP) and No. 2 fuel oil. Since 1986, the site has been managed by the EPA. The main contaminants of concern included PCP and chlorinated dioxins and furans. Dioxins and furans are found both on- and off-site.

Chlorinated dioxins and furans are the 75 polychlorinated dibenzodioxin (CDD) and 135 polychlorinated dibenzofuran (CDF) congeners, respectively. Of environmental concern are 17 CDD/CDF congeners with four or more chlorines. CDDs and CDFs are not created intentionally, but are the inadvertent by-products of man-made and natural processes. For example, detections of some CDD and CDF congeners in wood treatment facilities such as this one are linked to manufacturing impurities present in PCP.

A forensic investigation was conducted on the EPA's behalf to determine the nature and source of off-site dioxins and furans. Existing on-site and off-site soil dioxin/furan data was compiled into a geographical information system (GIS) database. A series of comprehensive quantitative analyses, including probability plot analysis of congener profiles, and principal component analysis of measured congener concentrations were conducted to address several key questions:

- Were the dioxins and furans detected in and around the site exclusively related to past site activities?
- Were there multiple CDD/CDF sources in and around the site? If yes, what are the characteristics of site-related versus ambient dioxins?
- Did the current soil data provide an adequate basis for delineation of site-related CDD/CDF?

The distribution of CDD and CDF congeners in environmental samples has been shown to correlate with their corresponding source—that is, they are dependent on the nature of the organic feedstocks and on the combustion conditions under which the CDDs and CDFs were formed. Distinct CDD and CDF congener profiles have been developed by EPA and others that support this observation (EPA, 1995; see Figure 16.8).

Forensic techniques for determining dioxin and furan sources rely on the comparative analysis of CDD/CDF congener profiles. Within this context the mixture of congeners in a sample serves as a source-specific signature or fingerprint.

Chemometric analysis of the available CDD/CDF congener data conducted as part of this investigation revealed three distinct sample groups, each of which had different CDD/CDF congener fingerprints (Figure 16.9). Those found on-site and those found in portions of a related drainage ditch located to the south of the site are referred to as group A and group B. These CDD/CDF congener profiles were distinctly different from those found in samples from the general, widespread off-site environs (referred to as group C). Figure 16.10 shows the geographic distribution of the three groups.

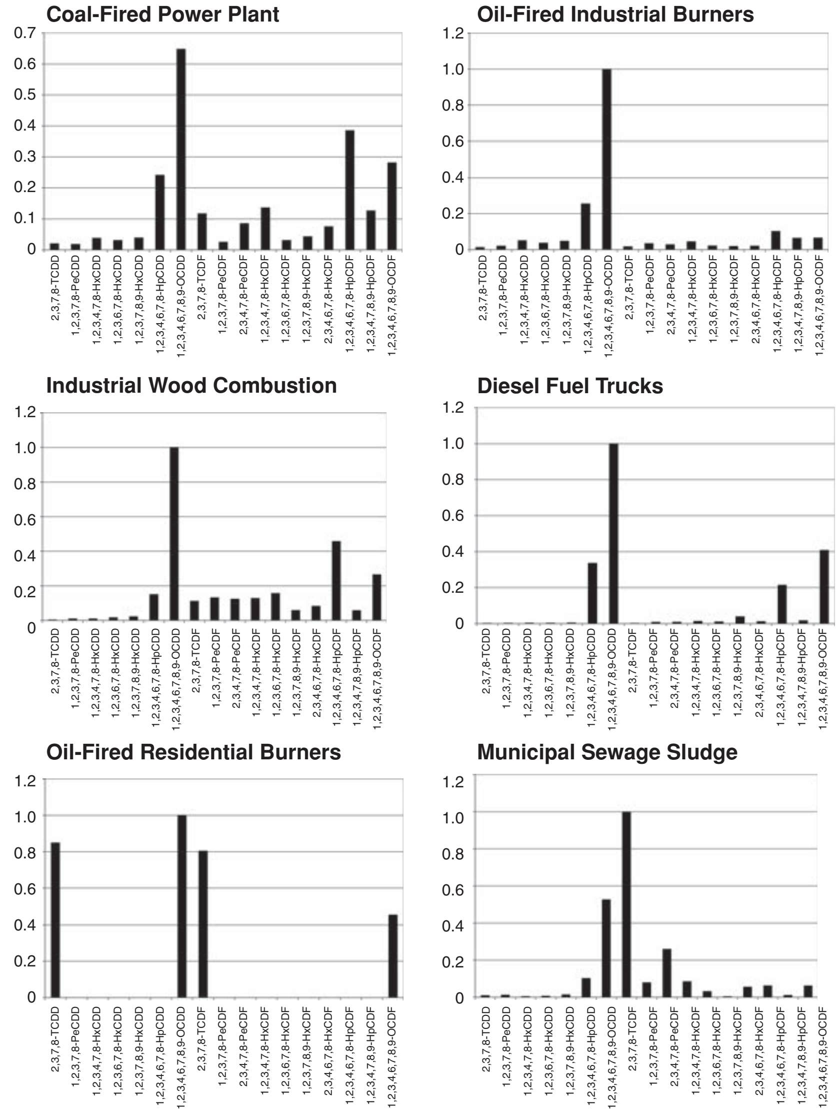

FIGURE 16.8

Chlorinated dioxin and furan congener patterns have distinctly different fingerprints, depending on the manner in which they are formed. *Source*: EPA, 2005.

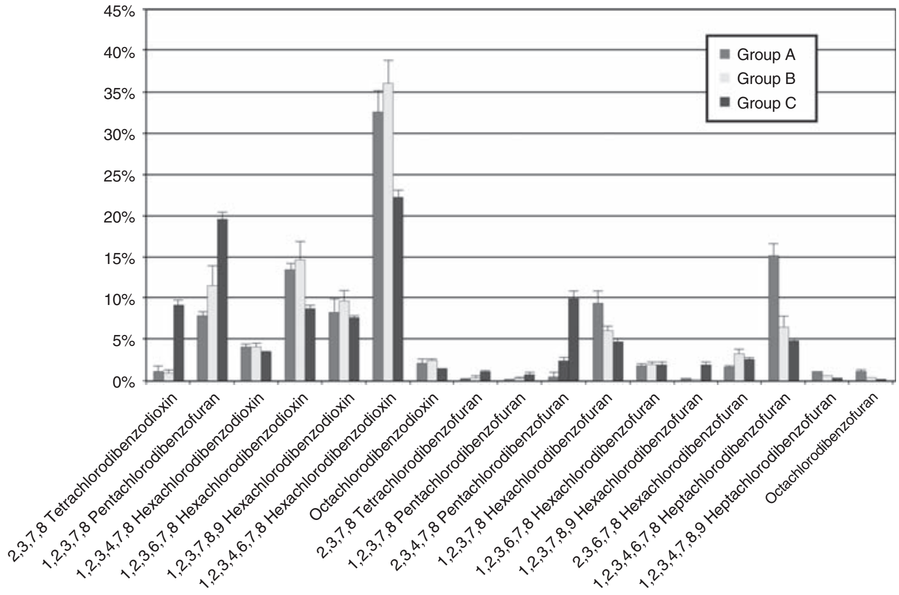

FIGURE 16.9

The dioxin and furan congener profiles for Site samples fell into three statistically defined groups (A, B, and C) that had distinctive congener profiles, indicative of different sources.

The group-A and group-B samples contained CDD/CDF patterns that were reconciled as site related, while the group-C samples contained dioxins and furans attributed to ambient conditions. Focused analyses of group-C sample data indicated a possible multiplicity of off-site ambient sources, including sporadic impact of past residential waste disposal practices such as backyard rubbish burning, as shown in Figure 16.11 (see page 346). Note that a local survey uncovered numerous potential off-site sources of CDD/CDF that explained these contaminants' ambient occurrence in the general vicinity of the site.

The ambient nature of the group-C dioxins and furans was further confirmed by the similarity of their dioxin profiles to those measured in sediments of Florida Panhandle Bay systems. However, this latter background data displayed patterns visually distinct from site-related dioxin profiles. Geospatially, the site-related group-A and group-B samples were "surrounded" by the ambient group-C samples. This forensic investigation supported the hypothesis that the currently available site characterization data provided an adequate basis for the delineation of the extent of site-related dioxins at and near the site. The CDD/CDF site impacts were identified by group-A and group-B samples; ambient conditions were designated by the group-C samples.

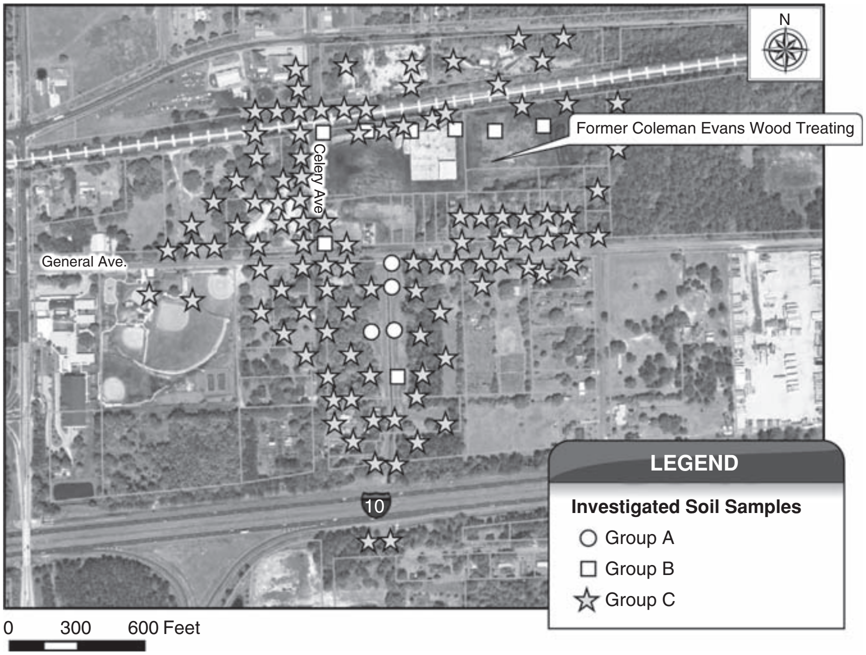

FIGURE 16.10

Geographic location of CDD/CDF groupings. Groups A and B were found on-site and in a site-proximal drainage ditch. Group C was found in samples throughout the ambient study area.

16.5 CONCLUSION

The nature, source, and age of chemical contamination are often pivotal questions raised in site investigations. Without answers to these questions, site redevelopment can be stalled for years or decades. Characterization of on-site and/or off-site contamination using conventional regulatory methods of chemical analysis are often inadequate for obtaining answers because they lack the specificity to appropriately classify the nature of the contamination. During the last 15 years, important strides have been made in the realm of chemical fingerprinting. Advanced methods of chemical analysis and data interpretation have been developed to provide investigators with high-resolution depictions of chemical contamination.

High-quality chemical fingerprinting can ascertain details of the makeup of chemical contamination to determine if contaminants arise from particular sources and to distinguish specific contaminants from other potential sources. Thus, it is a potentially powerful tool for investigators who seek knowledge of the nature, source, and attribution of chemical contamination and fair, expeditious pathways to site remediation and redevelopment.

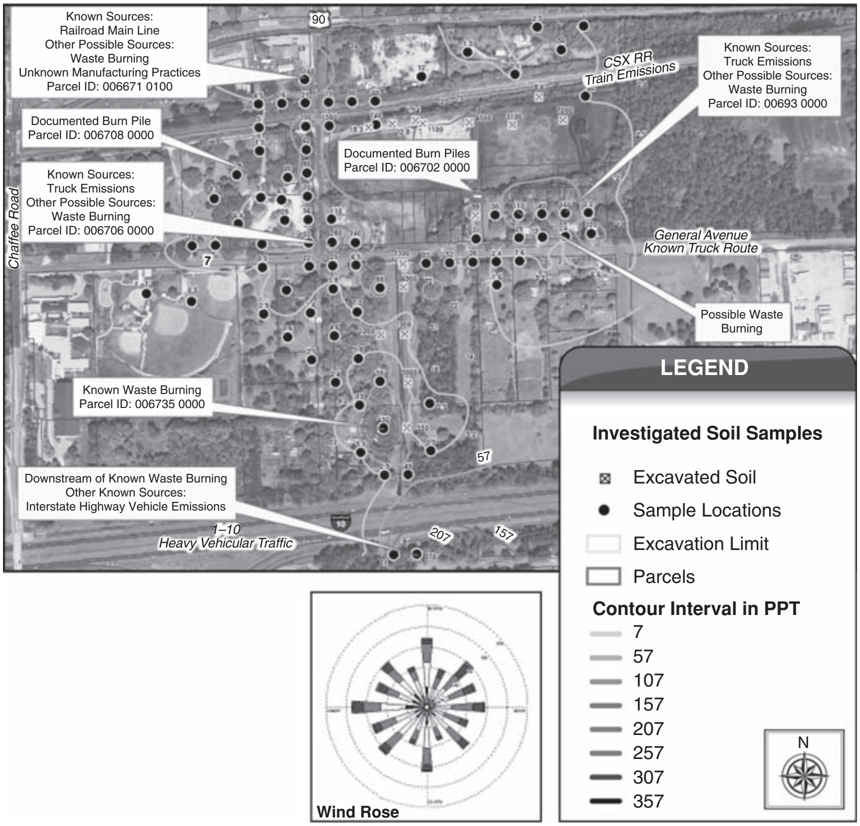

FIGURE 16.11

A local survey uncovered numerous potential off-site sources of CDD/CDF that explained the ambient occurrence of CDD/CDFs in the general vicinity of the Site.

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CHAPTER

17 Risk Assessment in Land Restoration

Kathryn A. Wurzel

It is essential in sustainable land restoration—from past industrial activities or excessive use of human-made chemicals—to evaluate the potential human health threats posed by contamination before, during, and after any actions taken to mitigate or control exposure and risk. Risk is associated with every decision, whether it is as simple as going to work (potential injury in a car accident) or staying home (potential loss of a job). In the United States, experience over the past thirty years of remedial action implementation has demonstrated that significant harm can ensue from the very activities designed to reduce harm.

Risk assessment is a tool that can be employed in the decision-making process at sites of environmental contamination to ensure that the remedy is not worse than the disease (Bacon, 2001). This chapter discusses risk assessments conducted within the framework of U.S. regulations and guidelines.

17.1 INTRODUCTION TO RISK ASSESSMENT

Risk is the probability of suffering harm. *Risk assessment* has traditionally been associated with determining the extent of remediation that is required for sites of environmental contamination. To determine the probability of human harm in the environmental context, the potency (toxicity) of and exposure to the contaminant (the dose) are assessed and quantified in this simple formula: Risk = Potency × Dose. A 16th-century chemist, Paracelsus, provided the basic rule of toxicology: "The dose makes the poison."

The presence of a toxic compound in the environment is not a risk if no one is exposed or if someone is exposed but the compound concentrations are very low. An analogy of how the dose makes the poison is the current practice of physicians recommending 81 mg of aspirin daily to reduce the probability of heart attacks and strokes. This small dose is not hazardous to your health. However, if you decide to take all 365 aspirin in one day because you fear you won't

DOI: 10.1016/B978-1-85617-797-9.00017-4

remember to take it daily, that dose then becomes a poison. It is the intersection of the dose (exposure) and the inherent toxicity of the contaminant that are addressed in the risk assessment process.

Risk Assessment Guidance for Superfund (RAGS), Human Health Evaluation Manual, Part A (EPA, 1989) provides guidance on human health evaluation activities that are conducted during the first step of the Remedial Investigation/Feasibility Study (RI/FS) process (baseline risk assessment). The *baseline risk assessment* is an analysis of the potential adverse health effects of hazardous substance releases from a site in the absence of any actions to control or mitigate these releases (i.e., no remedial action) under both current and reasonably foreseeable future land uses.

Baseline risk assessment contributes to the site characterization and the subsequent development, evaluation, and selection of appropriate response alternatives during the feasibility study. The results of the baseline risk assessment are used to determine if response action is necessary, to modify preliminary remediation goals (PRGs, developed in accordance with guidance provided in *RAGS, Part B, Development of Risk-based Remediation Goals*), to support selection of the "no-action" remedial alternative if appropriate, and to document the magnitude and primary causes of risk at a site.

Baseline risk assessments are site specific and therefore may vary both in detail and in the extent to which qualitative and quantitative analyses are used, depending on the complexity and particular circumstances of the site and the availability of applicable or relevant and appropriate requirements (ARARs) and other criteria, advisories, and guidance.

With the advent of electronic spreadsheets, the ability to produce risk estimates under multiple exposure scenarios and assumptions has resulted in more detailed quantification of risk during the baseline risk assessment. However, this detailed quantitative analysis has not been extended in practice to the determination of risk associated with implementation of remedial alternatives under the guidance of *RAGS, Part C, Risk Evaluation of Remedial Alternatives*. The lack of short-term risk quantification has resulted in the selection of remedies with short-term implementation risks that exceed the long-term risk goals by orders of magnitude. Sustainable remediation necessitates the evaluation of both short- and long-term risks to "ensure humanity meets the needs of the present without compromising the ability of future generations to meet their own needs" (UN, 1987).

EPA's risk assessment guidance documents were published in the late 1980s and early 1990s. The recent realization that the generation of carbon dioxide can adversely impact climate, and thus human health, requires new remedial alternative evaluation methodologies. Carbon dioxide generation is most appropriately classified as a short-term implementation risk for assessing remedial alternatives because it is associated with implementation activities, even though climate change has the potential to result in long-term effects.

17.2 BASELINE RISK ASSESSMENT PROCESS

The Comprehensive Environmental Response, Compensation, and Liability Act of 1980, as amended (CERCLA, or "Superfund"), has established a national program for addressing hazardous substances in the environment. The National Oil and Hazardous Substances Pollution Contingency Plan (NCP) is the regulation that implements CERCLA.

Human health evaluation is an integral part of the remedial response process defined by CERCLA and the NCP. Its goal is to provide a framework for developing sufficient risk information to assist in decision making at a contamination site. The specific goals of the human health evaluation process are as follows:

- To provide an analysis of baseline risks to assist in determining the need for action at sites of environmental contamination.
- To provide a basis for determining levels of chemicals that may remain at a site and that are adequately protective of public health.
- To provide a basis for comparing potential health impacts of various remedial alternatives.
- To provide a consistent process for evaluating and documenting public health threats at sites. (EPA, 1989)

A baseline human health risk assessment estimates the potential for adverse health effects from exposure to contaminants in various environmental media at a site under current and future land use conditions. The risk assessment process is composed of four steps (Figure 17.1):

Step 1. Data collection/data evaluation
Step 2. Exposure assessment
Step 3. Toxicity assessment
Step 4. Risk characterization

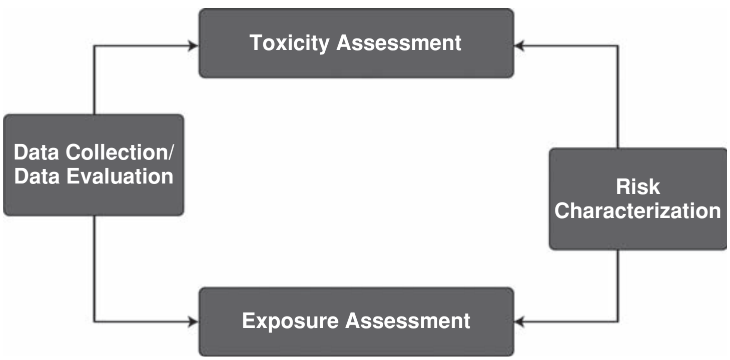

FIGURE 17.1

Baseline human health risk assessment process steps.

The *data collection/data evaluation* step identifies the contaminants of potential concern (COPCs). Data collected from the sampling activities is used to evaluate the risk to exposed populations from COPCs in environmental media under various exposure scenarios. The *exposure assessment* characterizes the physical setting of the site, identifies potentially exposed populations and potential exposure pathways, and calculates exposure concentrations. This information is combined to estimate the chemical intake for each potentially exposed population under each exposure scenario for current and future land use.

Exposure pathways are the various ways in which humans can come into contact with contamination present at a site (e.g., direct contact with soil or ingestion of groundwater). A complete exposure pathway must have a source of contamination, a mechanism of transport from the source to the environmental media (soil, groundwater, etc.), a point where humans come into contact with the contaminated environmental media, and a route of entry into the body (Figure 17.2). Figure 17.3 presents common exposure pathways encountered at sites of environmental contamination.

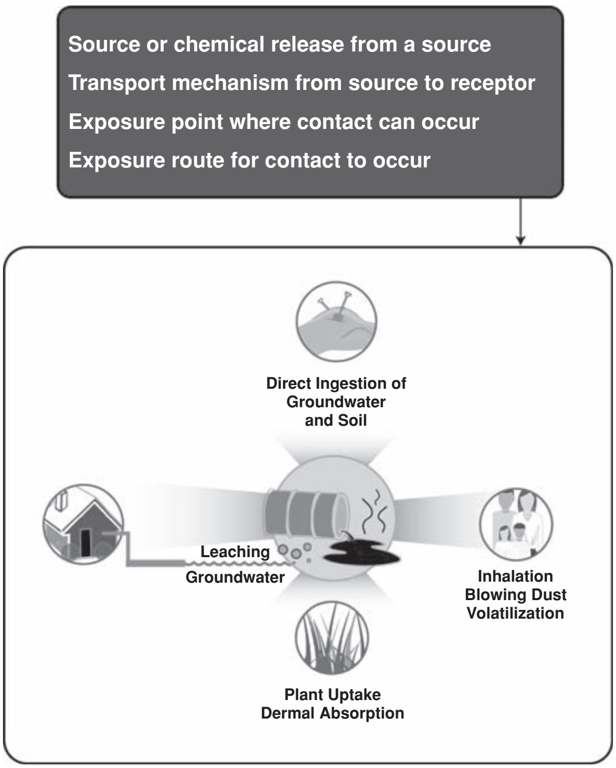

FIGURE 17.2

Components of complete exposure pathways.

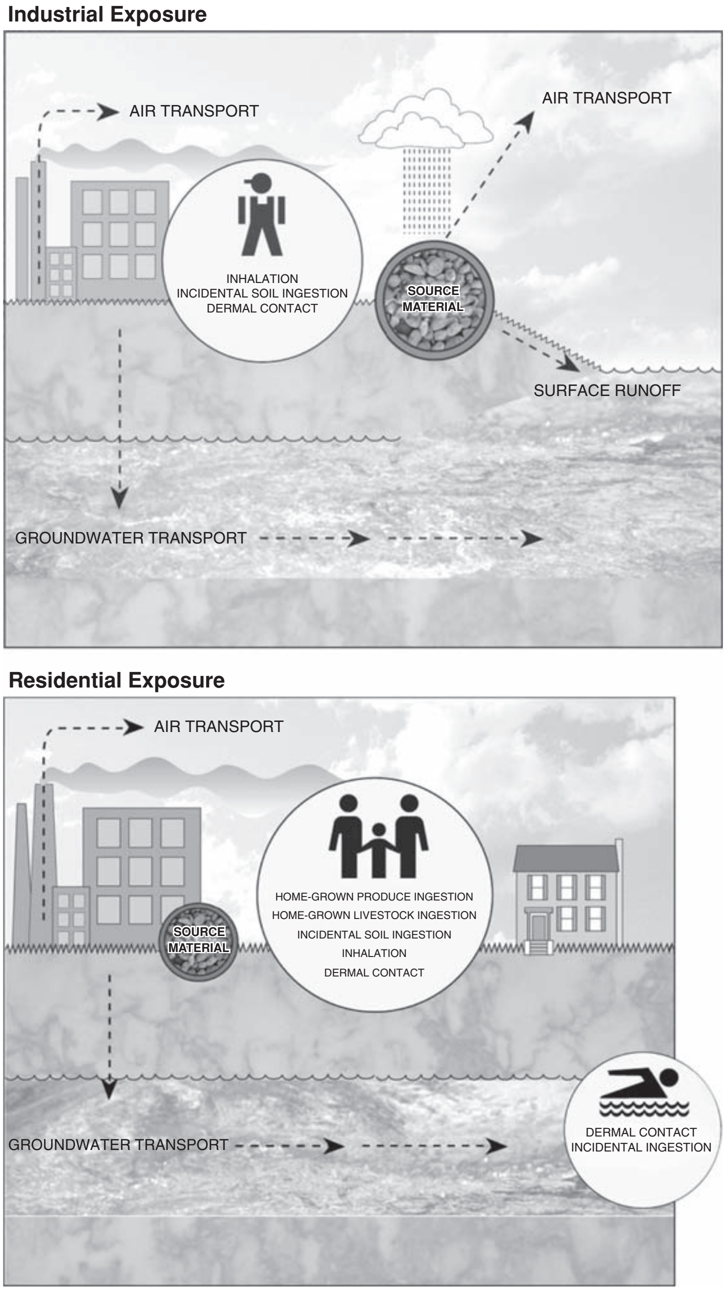

FIGURE 17.3

Exposure pathways.

The *toxicity assessment* is performed for each of the selected site COPCs. The EPA's Integrated Risk Information System (IRIS) is utilized to obtain toxicity values for use in risk assessment: *slope factors* for carcinogenic compounds and *reference doses* (RfDs) for noncarcinogenic compounds.

Risk characterization uses information obtained from the other three steps to quantify the risk from individual and multiple contaminants, to combine risks across exposure pathways, and to assess and present the uncertainty associated with the risk estimates. The estimated risks and their uncertainties are then used in decision making for determining the need for and type of remedial action for the site.

Risk assessment is generally conducted to evaluate the potential adverse human health effects associated with exposure to various environmental media, including soils, groundwater, surface water, sediment, and air. Consideration of other potential exposures such as ingestion of home-grown produce or local meat and fish is dependent on the site characteristics (potential for bioaccumulation in the food chain) and the potentially exposed populations (subsistence farmers and fishermen).

When human contact with the contaminants is plausible, the intake associated with such contact is estimated using health-protective assumptions. The risk assessment generally assumes a *reasonable maximum exposure* (RME) to contaminants at a site as an appropriate metric for estimating exposure and thus possible risk. The RME, which is defined as the highest exposure that is reasonably expected to occur at a site, is used to develop an estimate of exposure well above average but still within the range of possible exposures. An average exposure is also evaluated (*central tendency estimate*, or CTE). Depending on site conditions, potentially exposed populations, and available site-specific information, risk may be calculated for site-specific exposures in the baseline risk assessment.

NCP §300.430(e) states the following:

> *For known or suspected carcinogens, the acceptable exposure levels are generally concentration levels that represent an excess upper bound lifetime cancer risk to an individual of between 10^{-4} and 10^{-6} using information on the relationship between dose and response. The 10^{-6} risk level shall be used as the point of departure for determining remediation goals for alternatives where ARARs are not available or sufficiently protective because of multiple contaminants at a site or multiple pathways of exposure.*

This is interpreted to mean that if the baseline risk assessment determines that the excess lifetime cancer risk associated with the site exposure scenarios is within the risk range of 10^{-4} to 10^{-6}, no remedial action is necessary to provide adequate protection of human health. However, the remediation goal for sites requiring action is established at the 10^{-6} level of risk to ensure protection of human health following remedial action.

17.3 RISK EVALUATION OF REMEDIAL ALTERNATIVES

NCP §300.430(e) identifies nine criteria for evaluation of remedial alternatives. These are presented in Figure 17.4. The importance of risk in the selection of a remedy is evident in that several of the nine criteria involve the direct use of risk information. The criteria have been divided into three groups based on importance:

Group 1: Two threshold criteria. These must be met or the remedial alternative is eliminated from consideration based on the inability to protect human health or comply with ARARs.

Group 2: Five primary balancing criteria. These compare the alternatives that meet the threshold criteria. They take into consideration the permanence of the solution, the reduction in a contaminant source's toxicity, mobility or volume through treatment (e.g., incineration, stabilization, excavation), short-term effectiveness, ability to implement the remedy (technical practicability), and cost.

Group 3: Two modifying criteria. These are used to refine the selected alternative to gain agency and community acceptance, but their evaluation does not result in rejection of the selected remedial alternative.

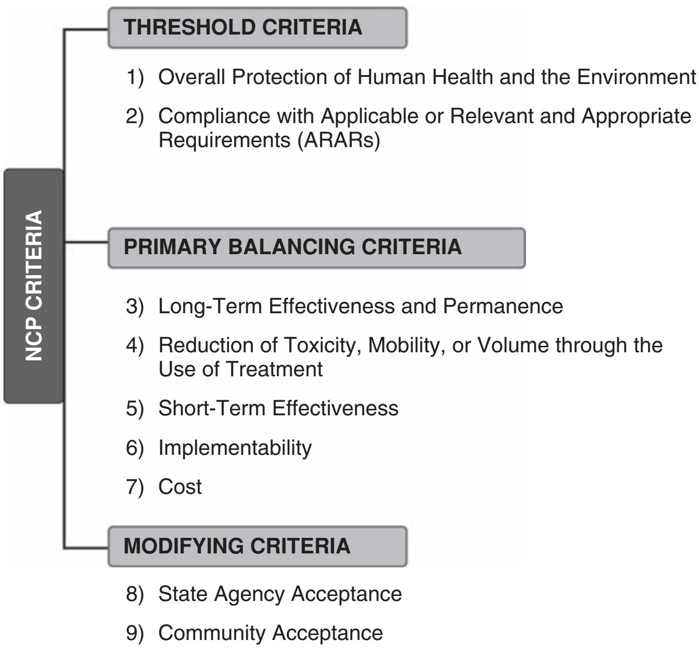

FIGURE 17.4

Criteria for evaluation of remedial alternatives.

Long-term human health risks associated with a remedial alternative are those that remain after the remedy has been implemented. They are determined by considering the post-remedy residual contamination (the goal of the remedial action is to attain an incremental increased risk level of 10^{-6}). The evaluation of the protectiveness of the remedy over time (permanence) is assessed in the remedial risk evaluation.

Short-term human health risks are those that occur during the implementation of the remedial alternative. Some remedies may take many years to complete, but the risks associated with their implementation are considered under the NCP to be short term. The same four-step process used in the baseline risk assessment is used in the short-term risk evaluation. The exposure assessment in the remedial alternative risk evaluation considers different *receptors* (potentially exposed populations), exposure pathways, and environmental media concentrations.

One of the major differences between the baseline risk assessment and the risk evaluation of remedial alternatives is the timing and duration of releases. The baseline risk assessment assumes that exposure to contamination at a site will occur unabated into the foreseeable future depending on the specific exposure scenario (i.e., residential or industrial). Because of the different activities that may occur during a remedial action, the timing, location, and concentrations of the contaminants may change over time and be limited to certain phases of work.

The receptors considered in the risk evaluation of remedial alternatives are both occupational and nonoccupational. *Occupational receptors* may be onsite remediation workers associated with site-related activities, treatment, and/or excavation of soil, as well as drivers of vehicles transporting materials for offsite disposal and importing backfill soils. *Nonoccupational receptors* are members of the general public who reside near the site and pedestrians, bicyclists, and motorists who may encounter trucks traveling to and from the site.

Health and safety plans are required for implementation of remedial activities at environmental contamination sites, but they do not assess the potential risks associated with the activity and they assume that all activities will be conducted in accordance with the plan. The risk and safety of transportation is not a part of the remedial risk evaluation as envisioned by the EPA, even though traffic accidents involving trucks present significant risks of injury and death.

17.4 QUALITATIVE AND QUANTITATIVE RISK ASSESSMENT OF REMEDIAL ALTERNATIVES

Evaluation of short-term risks for remedial alternatives can be either qualitative or quantitative. The need for quantitative analysis should be determined by whether the relative short-term or long-term risks are important considerations in remedy selection and whether there is high perceived risk to nearby communities. Figure 17.5 is an information box from *RAGS, Part C,* listing some of the factors that result in higher perceived risk. Close proximity to residential areas, high

FACTORS TO CONSIDER WHEN DECIDING WHETHER A QUANTITATIVE RISK EVALUATION IS NEEDED

The decision of whether to conduct a quantitative or qualitative risk evaluation depends on (1) whether the *relative* short-term or long-term effectiveness of alternatives is an important consideration in selecting an alternative and (2) the “perceived risk” associated with the alternative. The perceived risk includes both the professional judgment of the site engineers and risk assessors and the concerns of neighboring communities. Some factors that generally lead to a higher perceived risk are as follows:

- Close proximity of populations
- Presence of highly or acutely toxic chemicals
- Technologies with high release potential, either planned or “accidental”
- High uncertainties in the nature of releases (e.g., amount or identity of contaminants released) such as might exist with the use of certain innovative technologies
- Multiple contaminants and/or exposure pathways affecting the same individuals
- Multiple releases occurring simultaneously (e.g., from technologies operating in close proximity)
- Multiple releases occurring from remedial actions at several operable units in close proximity
- Releases occurring over long periods of time

If consideration of these (or other) factors leads to a high perceived risk for an alternative, a more quantitative evaluation, including emission modeling and/or detailed treatability studies, may be helpful in the decision-making process. For example, if one alternative considered for a site involves extensive excavation in an area that is very close to residential populations, then a more quantitative evaluation of short-term risks may be needed to evaluate this alternative. In addition, other factors, such as available data and resources, may affect the level of detail for these risk evaluations.

FIGURE 17.5

Information box from RAGS Part C.

release potential (such as fugitive dust or volatile emissions during excavation), and implementation schedules that result in releases over long periods of time are associated with high perceived risk.

Historically, there was little focus on the short-term effectiveness of various remedial alternatives in feasibility study evaluations. Reliance on development and implementation of site-specific health and safety plans *after* remedy selection limits the value of an implementation risk assessment during remedy selection.

As an example, a detailed evaluation of the potential implementation risk for a CERCLA site in Michigan conducted in the mid-1990s resulted in an amended Record of Decision (ROD) changing the remedy from excavation to capping in place, with other remedy components to protect groundwater and surface water (EPA, 2007). The potential for contaminated fugitive dust and volatile organic compound emissions in the residential community near the site was not evaluated in the original remedy selection process; on-site remediation worker risk was assumed to be controlled by personal protective equipment and health and safety procedures, and fugitive dust control measures were proposed during the excavation activities.

However, no calculations were performed during the original remedy selection process to determine if these measures would be sufficient to protect public health. The re-evaluation process revealed that, even considering 99 percent fugitive dust control efficiency, the offsite risk to residents was excessive and the excavation remedy did not comply with the requirement of short-term effectiveness.

The Michigan site serves as an example of the consequences of a qualitative evaluation of the risk associated with remedy alternatives. Only after the quantification of the risk from fugitive emissions during excavation was it evident that the qualitative assessment was insufficient. Reliance on assumptions of compliance can lead to the selection of remedies that result in unnecessary short-term risk to workers and the public without concomitant reduction in long-term risk.

17.5 CARBON DIOXIDE GENERATION AS A SHORT-TERM RISK

A near universal weakness in decision making for restoration of polluted land or water is the one-dimensional nature of risk assessment. The environmental risk of the target pollutant may be reasonably well assessed, but the consequence of the remedial action itself is seldom considered holistically. The pollution associated with cleaning up pollution is seldom taken into account.

For example, fuel consumption and carbon dioxide emissions traditionally were not included as metrics in the consideration of short- and long-term impacts under CERCLA. However, there is growing awareness in the scientific, regulatory, political, and business communities that the quality of decision making is enhanced when it includes consideration of environmental sustainability. The critical components of environmental sustainability are resource consumption and long-term irreversible environmental degradation associated with carbon dioxide emissions.

Representative of this awareness is the February 2003 commitment by four U.S. agencies (Department of Energy, EPA, Department of Transportation, and Department of Agriculture) to work with several major industrial sectors and the membership of the Business Roundtable to reduce greenhouse gas emissions in the next decade. Participating industry sectors include oil and gas production, transportation, and refining; electricity generation; coal and mineral production and mining; manufacturing (automobiles, cement, iron and steel, magnesium, aluminum, chemicals and semiconductors); railroads; and forestry products (EPA, 2009).

The generation of carbon dioxide from fuel combustion contributes to greenhouse gases in the atmosphere (water vapor, carbon dioxide, methane, nitrous oxide, ozone). These gases are essential in controlling the temperature of the Earth. The 2007 assessment report compiled by the Intergovernmental Panel on Climate Change (IPCC, 2007) observed that “changes in atmospheric concentrations of greenhouse gases and aerosols, land cover, and solar radiation alter the energy balance of the climate system" and concluded, "Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations." Increases in global temperature will alter ecosystems and have adverse impacts on human health. While these changes are considered long term, the generation of carbon dioxide during remediation activity can be most efficiently assessed under the scope of short-term risks prior to selection of a remedy.

Because carbon dioxide (CO_2) is generated during fuel combustion, fuel usage is directly related to CO_2 production. Remedial activities generally rely on the use of heavy equipment that requires significant fossil fuel usage. Details such as volumes of soil, extent of excavation, and general types of equipment used to complete tasks are usually available in the cost estimate documentation in the feasibility study. Once the equipment is identified, fuel usage data can be obtained and the estimate of CO_2 generation completed.

Although the impact of CO_2 on human health cannot be quantified in the same manner as the other short-term risk estimates (i.e., injury or deaths per number of individuals), other metrics allow for sustainability comparisons among remedial alternatives. Example metrics for evaluating the carbon impact of various remedial options are the number of trees necessary to sequester the carbon and the number of homes that generate an equivalent amount of carbon.

17.6 CASE STUDY

The following case study demonstrates the various issues that should be addressed in risk evaluation for remedial action. It compares three remedial alternatives for contaminated soil: in situ treatment, partial excavation/consolidation with a constructed cap, and complete excavation. Occupational and nonoccupational risk was evaluated as well as carbon generation. The time to implement the remedy was integral to the assessment because the duration of exposure is an important factor in the calculation of risk from exposure to contaminants in the environmental media. Implementation time also impacts public acceptance of a remedial alternative.

This study focuses on surface and subsurface soil contamination with an in situ treatment remedial option and two excavation scenarios. The partial excavation would relocate material for consolidation on-site with subsequent capping; only hazardous material would be transported and disposed off-site. Complete removal, resulting in off-site disposal of all contaminated material, would require additional material handling for excavation, on-site stockpiling, material loading, material transportation to a treatment, storage, and disposal facility, and final disposal in a landfill.

Soil excavation could result in significant fugitive dust emissions that may impact nearby residents. Fugitive dust modeling was conducted to assess the potential impact of the remedial options on an adjacent residential area. The greater the quantity of material excavated, the greater the emissions of fugitive dust. The location of the excavation area relative to the residential area correlated directly with the estimated risk of exposure to contaminated soil. The fugitive dust generation alone (irrespective of contamination that might be present in the soil) could result in adverse health effects, particularly if the area had been designated nonattainment for particulate matter. Therefore, in this case fugitive dust estimates were compared to the National Ambient Air Quality Standard for PM 2.5 (particulate matter less than 2.5 microns).

Although there are no labor statistics for injury or death specific to hazardous waste workers, statistics are available for heavy construction workers. These statistics, based on job classification, were used to estimate the onsite occupational risk unrelated to the presence of soil contamination (Hoskin and Planet, 1994). It was assumed that the site-specific health and safety plan identified the type of personal protective equipment required based on the level of contamination, and that the equipment was worn and maintained in accordance with standard practices. Figure 17.6 presents a summary of the occupational risks for the three remedial alternatives.

A major concern expressed by communities surrounding sites of environmental contamination is the potential for accidents involving truck traffic associated with remedial activities. The nonoccupational (general public) risk not related to site-specific contamination (i.e., risk other than exposure to contaminated fugitive dust) was estimated using statistical data obtained on injuries and deaths involving trucks and other vehicles, pedestrians, and bicyclists. Figure 17.7 provides a summary of the nonoccupational risks for the three remedial alternatives.

Comparison of the long-term risk goal of 10^{-6} and the short-term occupational and nonoccupational risks provides an assessment of the sustainability of the alternatives. As shown in Figure 17.8, the short-term risks are orders of magnitude greater than the long-term risk considered acceptable under the NCP following remedial actions at a site.

A useful means of comparing various risks is the Paling Perspective Scale (Paling, 1997), which provides data on common daily risks faced by average individuals. The right side of the scale represents absolutely certain risks (probability of 1.0); the left side shows highly unlikely risks (one in a trillion, or 10^{-12}) (Figure 17.9; see page 363). The risks calculated for occupational, nonoccupational, and long-term risks from the site under study were identified on the scale.

The short-term risks were calculated from *actual reported incidence and mortality rates* (actuarial data) for heavy construction workers (including truck drivers) and the public involved in accidents with commercial trucks. The estimated long-term risks were calculated for *hypothetical exposures* based on assumptions of reasonable maximum future exposures. The importance of hypothetical risk should be discounted even further relative to that of any actuarial risk. The conditions for the hypothetical may never come to pass. A decision based on a hypothetical long-term risk that excludes consideration of actuarial, certain, and short-term risk can be highly flawed. It is equivalent to making a commitment for a mortgage

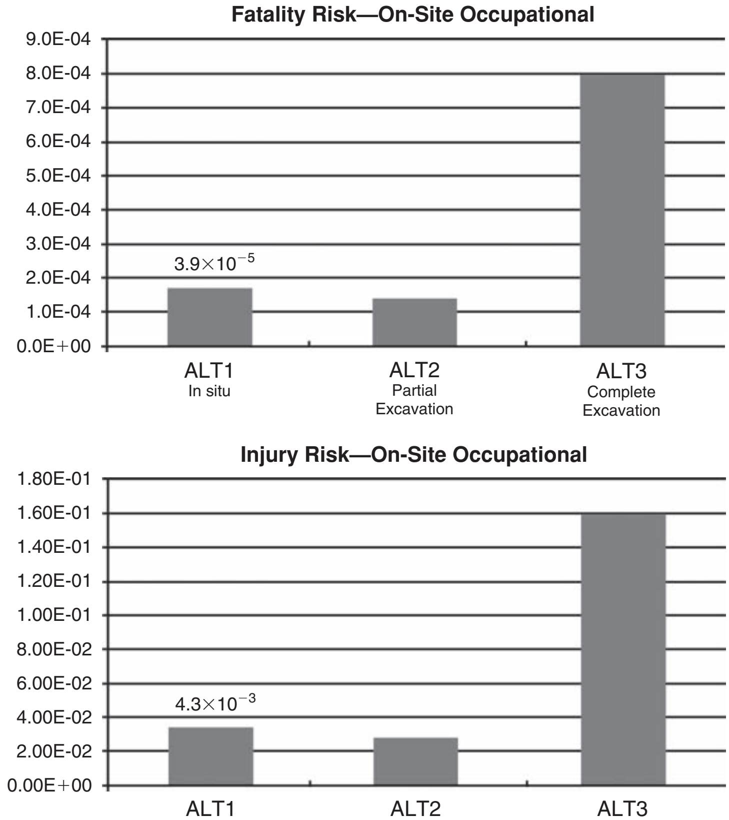

FIGURE 17.6

Estimated occupational risk of injury and death.

based on your potential income should you enroll in medical school and become a plastic surgeon, rather than based on what you earn at your present job at a fast-food restaurant. For our example, the risk evaluation for remedial alternatives demonstrates that the known risks were greater than the potential future risks for this site.

In addition to the estimation of short-term occupational and nonoccupational human health risks, the generation of carbon dioxide was calculated for each remedial alternative. The calculation of carbon emissions is shown in Figure 17.10. The complete excavation scenario had a much higher equipment usage demand than partial excavation and an even more significant fuel demand due to transportation of all material offsite. The in situ option did not require soil excavation or offsite disposal of material, so the fuel requirements were markedly lower.

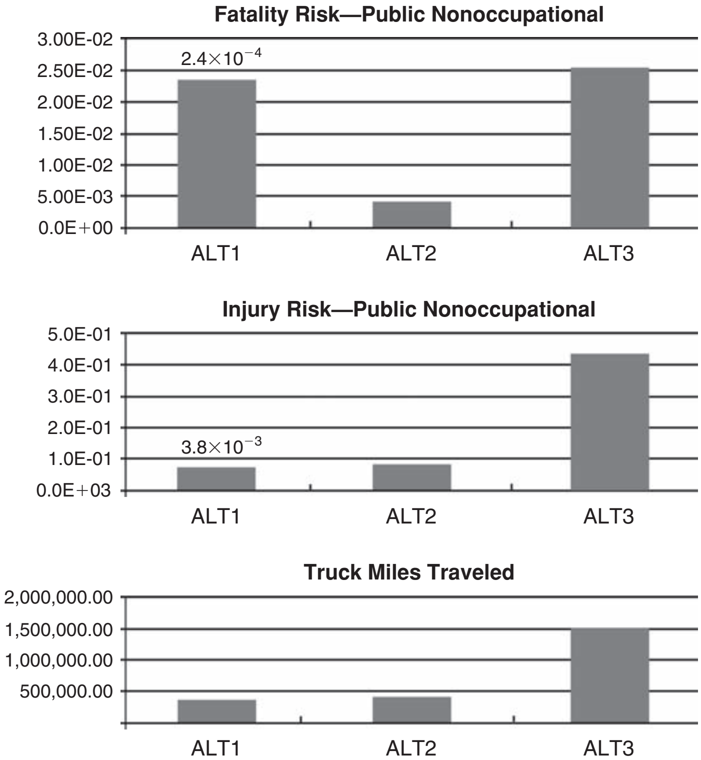

FIGURE 17.7

Estimated nonoccupational risk of injury and death.

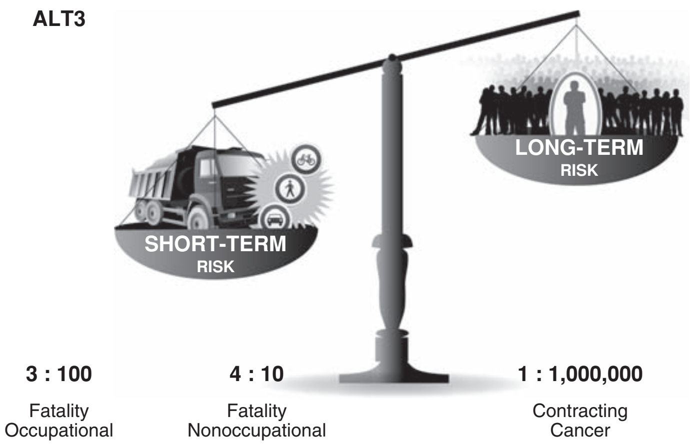

FIGURE 17.8

Comparison of short-term risks to long-term risks for each remedial alternative.

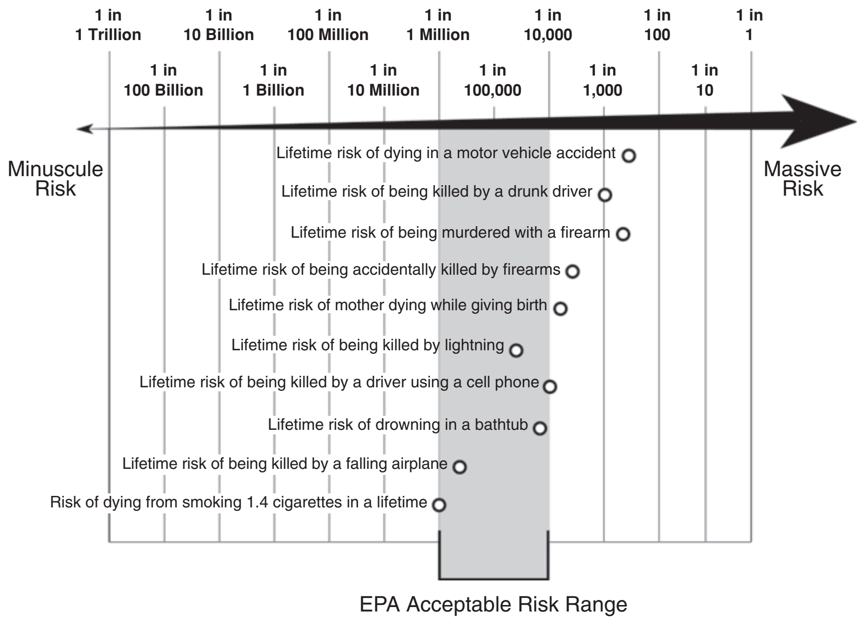

FIGURE 17.9

Paling Perspective Scale. *Source*: Adapted from the Paling Perspective Scale © 1992, in "Dealing with the Real Risks to Local Communities," John Paling, 1998.

Figure 17.11 provides a sample summary spreadsheet with CO_2 generation in tons, allocation of CO_2 generation by activity, and number of trees or acreage required to sequester the carbon. Trees and acreage were used for comparison of the remedial alternatives, as these metrics are more readily understood than metric tons of CO_2. Figure 17.12 presents the forest acres required to sequester the CO_2 generated by remedial alternative three.

The results of the short-term risk evaluation are summarized in Figure 17.13 (see page 366), which shows tons of CO_2 generated, acres required for carbon sequestration, time to implement remedy, occupational risk, nonoccupational risk, and fugitive dust emissions. The in situ treatment had the lowest carbon generation and short-term human health risks due to contaminant exposure.

Both the occupational and the nonoccupational injury and death risks are directly related to the miles traveled for material disposal. This is true as well for CO_2 generation. The case study demonstrates that quantitative evaluation of risk for remedial alternatives results in the selection of an alternative that minimizes the off-site transportation component and has the greatest short-term effectiveness while providing adequate protection of human health in the long term.

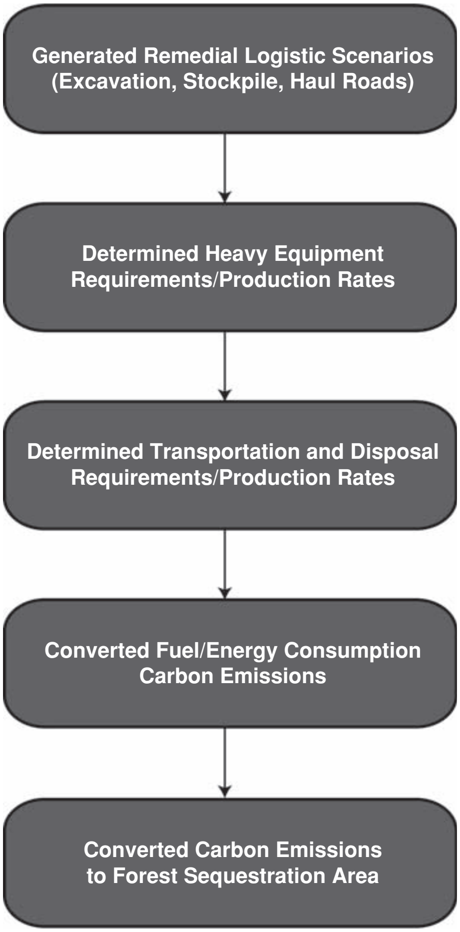

FIGURE 17.10

The carbon emission calculation process.

17.7 CONCLUSION

As demonstrated in the case study just described, decisions associated with managing or mitigating health risk in land use can have unintended consequences. The use of quantitative risk assessment is a decision consequence analysis task.

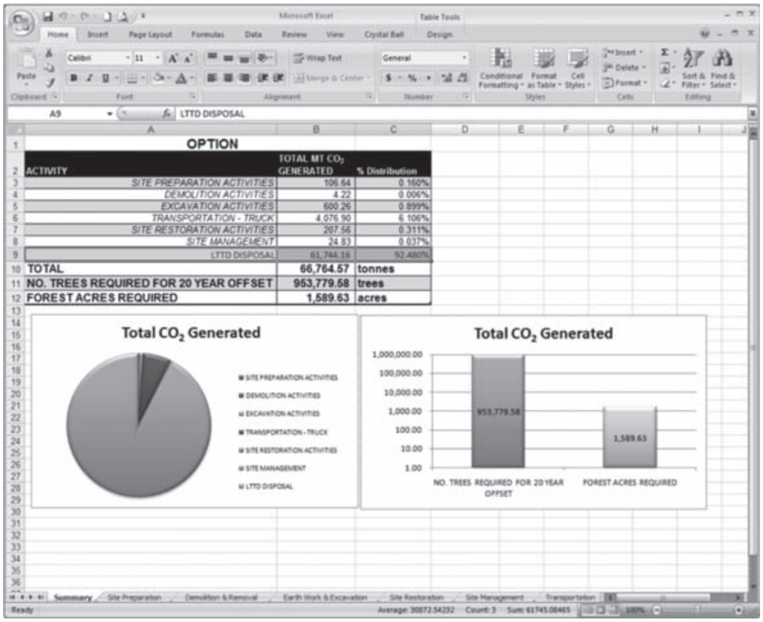

FIGURE 17.11

Sample carbon emission spreadsheet.

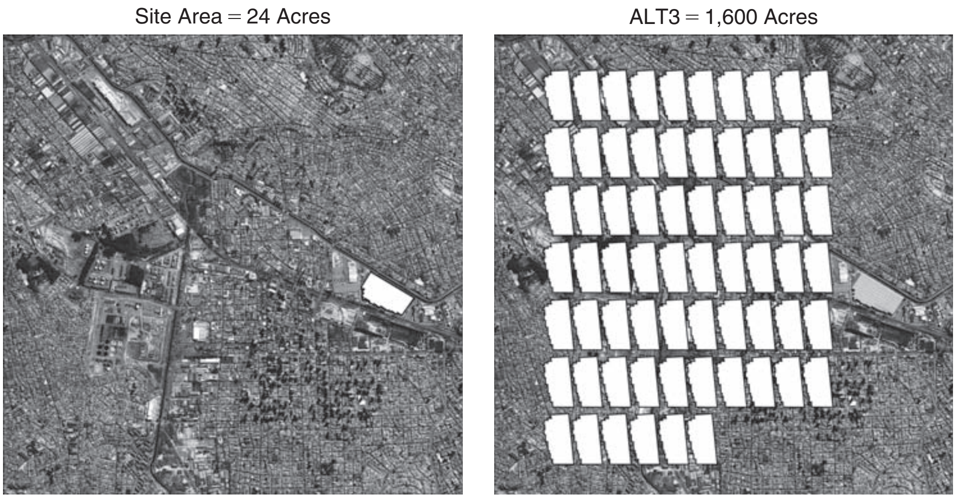

FIGURE 17.12

Forest acres required for sequestration.

	Total Tonnes CO_2	Forested Acreage	Time to Implement	Occupational Risk	Non occupational Risk	Fugitive Dust (PM 2.5) Generation
Alternative 1 In situ treatment	274	7	4 Months	*Fatality* 4:100,000 / *Injury* 4:1,000	*Fatality* 2:10,000 / *Injury* 4:1,000	Background exceeds 24 hr NAAQS
Alternative 2 Partial excavation and capping	7,7251	173	4 Months	*Fatality* 1:10,000 / *Injury* 3:100	*Fatality* 4:1,000 / *Injury* 6:100	3 × background exceeds 24 hr NAAQS
Alternative 3 Complete excavation	66,765	1,590	1.5 years	*Fatality* 1:1,000 / *Injury* 2:10	*Fatality* 3:1,000 / *Injury* 4:10	3 × background exceeds 24 hr NAAQS

FIGURE 17.13

Summary of short-term risks.

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CHAPTER

A Case Study of Reuse and Conservation of Water during Resource Management: Resolution Copper Mining

18

Joel Kimmelshue

18.1 BACKGROUND AND SUMMARY

Resolution Copper Mining (RCM) in Superior, Arizona, will have excess water for three to four years from the dewatering of an existing mine. The New Magma Irrigation and Drainage District (NMIDD) in central Arizona will recover over 6,000 acre-feet (AF), or approximately 2 billion gallons, of water from an RCM project. Resolution Copper is removing approximately 2.5 billion gallons of water from an existing mine shaft. The water is being treated at the mine site to remove metals and adjust its pH before it is transferred by gravity through a new pipeline built by RCM directly to the NMIDD. The water will then be blended at an approximate 1:10 ratio with Central Arizona Project (CAP) water (ten parts CAP water to one part mine water) before introduction into the system to be used for crop irrigation.

At the time of writing, the project has been delivering blended water to the growers for approximately four months. These activities are expected to continue for a total of three to four years. Substantial decision making went into the final end use of the treated mine water. Options included discharge to an adjacent stream, reverse osmosis, trucking of water, and agricultural irrigation. Agricultural irrigation was chosen because it provides a beneficial end use and it is cost-effective.

Successful use of RCM's water for irrigation depends on the water quality resulting from blending it with CAP water. The NMIDD can use the blended water for irrigation if the concentration of constituents is suitable for the crops grown in the district. These crops include alfalfa, cotton, wheat, sorghum, and turf grass (sod).

Decision makers carefully evaluated whether blending RCM and CAP water at a ratio of approximately 1:10 would result in water that was suitable for irrigation of

DOI: 10.1016/B978-1-85617-797-9.00018-6

alfalfa, cotton, wheat, sorghum, and turf grass. Its suitability is based on the following attributes:

- Agronomic constituents within published threshold values for irrigation water quality of cotton, alfalfa, wheat, sorghum, and turf.
- A finite duration of the intended full-scale program (three to four years).
- An inherently large leaching fraction (LF) associated with the surface irrigation methods used that will maintain acceptable root zone salinity levels.

Once a data set is created that correlates soil and water quality, additional monitoring information will be used to optimize the blending rates.

The water from RCM increases by approximately 10 percent the water supplied to the normal NMIDD diversion from the CAP Canal for System C. This provides additional flexibility and a possible increase in irrigated acreage in this part of the district or replacement of water in System C for use in other areas. The additional water is also important, as water supplies continue to be in high demand because of increased use and unpredictable rainfall.

The NMIDD signed a memorandum of agreement with RCM for the water transfer project. The agreement involved five parties working cooperatively to ensure safe treatment, transfer, and utilization of the water for crop irrigation. The five parties include:

- RCM
- NMIDD
- Growers in the NMIDD
- The University of Arizona (UA)
- The NewFields Companies consulting firm

The common motivating force for working on this project is the efficient utilization of water, which is considered the "lifeblood" for all living and working in the desert Southwest. It is imperative that none of this water be wasted and that no negative environmental impact is caused by its removal from the mine.

Based on initial estimates from water quality data gathered as the water is extracted from the mine, treated, and blended, it was determined that a 1:10 blending ratio would provide water that would be safe for use in agricultural crop production. To confirm this determination, the water chemistry is monitored very carefully as it is introduced in the NMIDD. It is analyzed daily as it is delivered and blended, after blending, and at several district delivery points. NMIDD soil and plant tissue samples are also collected on a regular basis each season and will be for the duration of the project to monitor the chemical properties for all water, soil, and crop components. Climatic conditions, irrigation practices, and crop water demand will be tracked.

In any desert irrigation system, caution must be exercised and salinity and sodium hazards must be carefully managed. Thus, it is important to note that the salinity hazard in this project is low, particularly considering that the estimated leaching requirement is 24 percent and that the actual LF employed across the NMIDD is approximately 40 percent.

18.2 CROP SUITABILITY AND APPROPRIATE USE OF BLENDED WATER

Water quantity and quality were analyzed to evaluate the suitability of RCM/CAP blended water for irrigation and to determine the benefits of using it. The soils, crops, and surrounding environment in the proposed use area, and the irrigation supply that would result from the addition of the blended RCM/CAP (1:10 ratio), appeared to be suitable for alfalfa, Bermuda grass, cotton, and rye grass, for the following reasons:

- The sodium hazard is relatively low, indicating that the potential for creating sodic soils is very low. The ratios of calcium to magnesium and of calcium and magnesium to sodium are suitable for irrigation.
- Chloride is well below the thresholds of the relevant crops.
- The salinity hazard is low, especially considering that current irrigation practices result in an approximate 40 percent LF, which is nearly double the 24 percent leaching requirement required for alfalfa, the most salt-sensitive crop grown.
- The relatively short duration of application proposed for this water (three to four years) indicates that salinization is unlikely. Any use of this water beyond two years will be additionally monitored by UA and NewFields to ensure no influence on crop growth or soil quality.
- Sulfate is within the normal range expected in irrigation water.
- Soils in the proposed NMIDD use area appear to be suitable, as determined from general soil descriptions and current cropping and irrigation practices.
- RCM water benefits the NMIDD by creating a free supply of additional water to fulfill district farmers' water needs. This steady supply of water will be especially helpful during periods of rainfall deficit.

18.3 WATER SUPPLY

Water is currently diverted from the CAP canal in response to crop demand in the NMIDD. Figure 18.1 provides the relative monthly demand from 2002 through 2006 for the entire diversion. The water distribution shown indicates that the bulk of the water is being diverted from March through September. Because of variations in water diversions, the RCM supply line will need to be flexible to maintain a 1:10 RCM/CAP blending ratio. Some variability is expected; however, the ratio is being managed on a monthly and even a weekly basis to ensure that sensitive crop

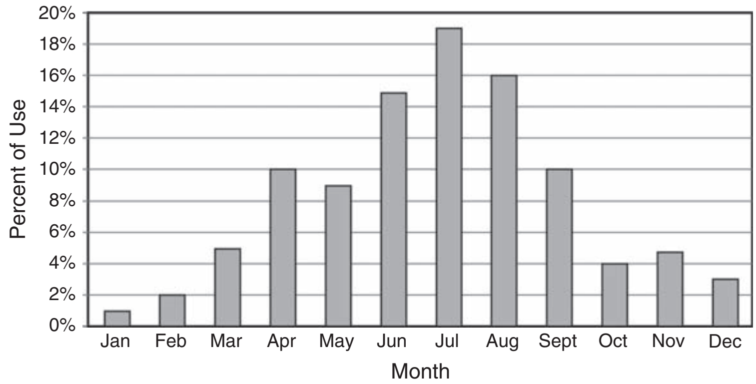

FIGURE 18.1

Five-year average (2002–2006) of relative agricultural water diversion by month for C-system. *Source*: *www.cap-az.com*.

NMIDD AVERAGE ANNUAL DIVERSION AND FLOW FOR B- AND C-SYSTEMS			
Resolution Copper Mine Water Quality for Irrigation in New Magma Irrigation and Drainage District			
System	**Average Annual Diversion (ac-ft/yr)**	**Normal Winter Flow Range (cfs)**	**Normal Summer Flow Range (cfs)**
B-System	**8,000 (+/– 1,500)**	**0–10**	**15–30**
C-System	**25,000 (+/– 3,000)**	**5–20**	**50–100**
Total	**33,000 (+/– 4,500)**	**5–30**	**65–130**

FIGURE 18.2

NMIDD average annual diversion and flow for B- and C-systems. *Source*: Personal communication with Bill Van Allen, NMIDD, General Manager.

development periods (e.g., spring germination) are not affected by lower water quality resulting from a higher ratio.

Two of seven NMIDD turnouts from the CAP canal were visited and considered for their potential as blending sites. The quantity and flow of diversion of these turnouts were quantified (Figure 18.2). One turnout (C-system) was directly adjacent to the expected path of the pipeline delivering water from RCM to NMIDD along a railroad right of way and so became the preferred blending point. The C-system delivers approximately 25,000 acre-feet per year at a maximum flow of approximately 100 cubic feet per second (cfs). The maximum capacity of the RCM supply pipeline is not expected to exceed 6 cfs, or 2,500 gallons per minute (gpm). Therefore, it will likely be necessary to design and manage the pipeline for varying flows to maintain a fairly consistent 1:10 blending ratio during off-peak irrigation months.

As previously mentioned, the project is expected to take place over a period of three to four years, beginning in March 2009. Project duration depends on the rate of dewatering, which in turn depends on the amount of water that can be received by NMIDD. Potential acceleration of the project is contingent on the following factors:

- Addition of the B-system irrigation area or other system fields that would increase the land area receiving water.
- Conversion of fallow land to irrigated crop land.
- Changes from crops with shorter seasons (annuals) and lower water requirements to crops with longer seasons (perennials) and higher water requirements.
- Addition of winter crops that are grown between main season crops when the land is usually left fallow.

These factors, which are largely dependent on grower preferences, will significantly determine how much water is used.

18.4 LOCATION

The project location extends from the Resolution Copper Mine in the historic Pioneer Mining District, approximately three miles east of Superior, Arizona, to the NMIDD near Queen Creek, Arizona—an approximate distance of 27 miles. The mine and the district are connected by a pipeline that delivers treated mine water. Currently, only the C-system irrigation area, with approximately 4,500 cropped acres, receives the water. Other irrigation systems within NMIDD (such as the B-system) may be added during the project, which will in turn increase the dewatering rate of the mine.

18.5 SCOPE OF WORK ACTIVITIES

The RCM Dewatering and Irrigation Project is primarily designed to deliver water suitable for blending with NMIDD CAP water for crop irrigation. Managing the water quality and ensuring that crop production is maintained at optimal levels are the main purposes of the project. To this end, project activities include the following:

- Informing NMIDD growers of project operations.
- Monitoring mine, CAP, and blended mine/CAP water quality.
- Managing and controlling the amount of treated mine water blended into CAP water.
- Monitoring soil and plant tissue health through routine field sampling.

Task Number	Task Name	Duties	Timing/ Frequency	Estimated Labor Hours
		Quarterly Soil Sampling		
1.1	**Prepare Supplies**	Collect/prepare supplies as needed, including map, push probe, buckets, sampling bags with labels, chains of custody, safety supplies. Coordinate with UA to ensure sampling protocol is followed and to submit ETA of samples.	One week prior to sampling.	**12 hrs** per sampling event
1.2	**Collect Samples**	Collect composite soil samples, fill out chains of custody, record location of samples, take photos if relevant, record relevant information such as date, time, weather conditions, etc.	2nd month of each quarter (February, May, August, November). If weather does not permit, sampling may be done during last month of quarter.	**100 hrs** per sampling event
1.3	**Deliver Samples**	Coordinate with UA staff and deliver samples to sample pickup location specified at UA, Tucson, AZ. Submit chains of custody and ensure they are signed.	1st two weeks of last month in quarter. If weather does not permit, deliver samples during last two weeks of quarter, or ASAP.	**12 hrs** per sampling event

FIGURE 18.3(a)

Tasks and estimated level of effort of regular sampling events for NMIDD field sampling staff (excluding background sampling).

- Monitoring field and climate conditions by maintaining continuous field logs.
- Providing growers access to project data on water, soil, and plant tissue.
- Providing agronomic consultation on crop production issues related to fertility, pests, weather, and the like.

Figures 18.3(a), (b), and (c) provide a summary of the major tasks for this multi-year sampling program, as well as duty types, timing and frequency, and labor estimates.

18.6 GROWER INFORMATION PROGRAM

Coordination with growers ensures that project operations are successful and that the dewatering activities occur in a timely manner. In order to maintain complete confidence in the project and in the monitoring program, a series of documents describing project operations and lines of contact have been provided to growers.

Task Number	Task Name	Duties	Timing/ Frequency	Estimated Labor Hours
Periodic Tissue Sampling				
2.1	**Prepare Supplies**	Collect/prepare supplies as needed, including map, cutting utensil, buckets, sampling bags with labels, chains of custody, safety supplies. Coordinate with UA to ensure sampling protocol is followed and to submit ETA of samples.	One week prior to sampling.	**12 hrs** per sampling event
2.2	**Collect Samples**	Collect composite soil samples, fill out chains of custody, record location of samples, take photos, record relevant information such as date, time, weather conditions, etc.	Sampling period depends on growth stage of crop. For simplicity and scheduling, this scope anticipates one quarterly sampling the 1st month of each quarter (January, April, July, October). If weather does not permit, sampling may be done during 2nd month of quarter.	**100 hrs** per sampling event
2.3	**Deliver Samples**	Coordinate with UA staff and deliver samples to sample pickup location specified at UA, Tucson, AZ. Submit chains of custody and ensure they are signed.	1st two weeks of 2nd month in quarter. If weather does not permit, deliver samples ASAP. An effort needs to be coordinated between field sampling staff and UA to have plant tissue samples analyzed in time for data to be used in quarterly reports; however, this may not always be possible.	**16 hrs** per sampling event

FIGURE 18.3(b)

A pamphlet containing background information about the project and the monitoring program has been published, as has a list of contacts for each cooperator involved. Growers have been advised to direct their questions and concerns to the NMIDD field sampling coordinator.

18.7 DATA ACQUISITION, MANAGEMENT, AND COMMUNICATION

This section provides details on data acquisition, management, and communication for the RCM Dewatering and Irrigation Project. An overview of project cooperator responsibilities is provided in Figure 18.4.

Task Number	Task Name	Duties	Timing/ Frequency	Estimated Labor Hours
		Water Quality Sampling		
3.1	**Prepare Supplies**	Collect/prepare supplies as needed, including bottles, detergents, decontamination water, chains of custody, etc. Coordinate with NewFields and UA to ensure sampling protocol is followed and to submit ETA of samples.	Monthly/Quarterly	**8 hrs** per sampling event
3.1	**Collect Samples**	Collect composite soil samples, fill out chains of custody, record location of samples and other relevant information such as date, time, weather conditions, etc. Take photos and record relevant information such as date, time, weather conditions, etc.	Monthly/Quarterly	**8 hrs** per sampling event
		Telemetry System Maintenance		
4.1	**Telemetry System Checks**	Check data loggers and power supplies for vandalism, proper operation. Inform designated responsible person if attention is needed.	Daily	**2×/wk @ 2 hrs each × 4 wks = 16 hrs/mo**
4.2	**Calibrate pH Meter Monthly and Other Sensors as Needed**	It is anticipated that pH sensors will need monthly calibration; however, pH and other sensors may need calibration more or less frequently, depending on water quality conditions.	Monthly	**2×/month @ 4 hrs each = 8 hrs/mo**
		Crop Status and Field Operations Log		
5.1	**Field Operations Log**	Log weekly grower field operations on fields receiving RCM water, such as planting, fertilizer, and pesticide applications, crop growth stage, weather, desiccating, cutting, and harvesting operations, etc.	Weekly	**2 per week at 2 hrs each = 16 hrs/mo**

FIGURE 18.3(c)

Type of Monitoring	Cooperator Responsible for Collection	Cooperator Responsible for Data Analysis	Cooperator Responsible for Data Collection and Management	Cooperator Responsible for Reporting
Water				
Continuous	NewFields	NewFields	NewFields	NewFields
Manual Sampling	NMIDD	University of Arizona	NewFields	NewFields/UA
Soil				
Manual Sampling	NMIDD	University of Arizona	NewFields	NewFields/UA
Plant Tissue				
Manual Sampling	NMIDD	University of Arizona	NewFields	NewFields/UA
Field Operations/Crop Status				
Manual Sampling	NMIDD	University of Arizona	NewFields	NewFields/UA
Manual Sampling	NMIDD	University of Arizona	NewFields	NewFields/UA
Land Use Mapping				
Manual Sampling	NMIDD	University of Arizona	NewFields	NewFields/UA

Notes: All data will also be included in annual reports. NewFields and UA are jointly responsible for reporting water quality, soil, and plant tissue data from manual sampling; NewFields is responsible for preparing, drafting, delivering, and finalizing reports, and UA is responsible for technical review of these reports before they are finalized.

FIGURE 18.4

Cooperator responsibilities for data collection, management, and reporting.

18.7.1 Overview of Telemetry System

An automated remote telemetry system will be used to measure, store, and transmit sampling data. The components of the system are as follows:

1. Water flow for treated RCM water is measured at the water treatment facility (WTF) and pumping station.
2. Treated RCM water quality (temperature, TDS, pH) is measured via sondes at the WTF and pumping station, and downstream of the pumping station.
3. CAP water quality data is obtained from a water quality sensor (sonde) upstream of the pumping station.
4. Water quality sondes send data to a data logger for storage.

5. The data logger sends data (via cellular modem) to the data-housing software at RCM for data management.
6. The NMIDD enters a daily water order (CAP quantity) into data-housing software.
7. The data-housing software evaluates water quality (RCM and CAP) and quantity data (CAP) to automatically calculate the volume of treated RCM water needed to fulfill the NMIDD demand.
8. The data-housing software sends an e-mail alert to the WTF operator and pertinent project cooperators so WTF pumps can be adjusted, if needed.
9. Field sampling staff enter manual sampling data (soil, tissue, water) into the data-housing software.
10. The data-housing software sends data to the Web Data Center Web site for project cooperator and grower access.

18.7.2 Salinity of Treated Mine Water and CAP Water

The quality of the CAP water is not expected to change significantly; however, it will continuously be monitored for salinity, pH, and temperature. Preliminary analysis of RCM water indicates that a 1:10 blending ratio is a conservative estimate of the ratio required to produce water that is safe for crops grown in the NMIDD. However, water quality will likely change as the mine shaft is dewatered, and salt concentration may increase or decrease. Daily water quality monitoring at the WTF and at the end of the pipeline will indicate these changes, and the blending ratio will be modified accordingly.

18.7.3 Amount of Water Released by CAP

The amount of water released by CAP on a daily basis varies in response to daily water orders submitted by the NMIDD. Every morning (when irrigation is needed), growers call in their water orders for the next day to the NMIDD manager. When these orders are tallied, the NMIDD manager sends the collective water order to CAP for the next day. This process is usually completed by approximately 10:00 every morning. CAP Canal water is released at approximately 5:00 to 6:00 every morning.

18.7.4 Blending Protocol

The amount of treated mine water that is released and ultimately blended with CAP water is controlled by adjusting water release valves at the WTF before the water enters the pipeline. Because the water released into the pipeline takes approximately four hours to reach its destination at the CAP canal, adjusting the water release valve at least eight hours in advance, according to daily measurements of the mine water's salinity, results in appropriate blending at the end of the pipeline.

Three factors determine the amount of water that can be released from RCM to achieve the 1:10 blending ratio. In other words, to calculate the amount of water that RCM can release, three values must be known:

- CAP water quantity
- CAP water quality
- Treated RCM water quality

Components in the telemetry system (e.g., the data-housing software) can also perform calculations with the data it receives. In this way, the calculation is performed without human error. An overview of the blending protocol is provided in Figure 18.5. This protocol will be conducted as follows:

1. The data-housing software receives daily treated RCM and CAP water quality data.
2. The NMIDD logs on to the data-housing software and enters its water order (CAP water quantity) for the following day between approximately 9:00 and 10:00 in the morning.
3. The data center uses the most recent treated RCM water quality data (24-hour average), CAP water quality data (24-hour average), and CAP water quantity to calculate the quantity of treated RCM water that should be released the following day to achieve the correct blending ratio.
4. The data center archives all data inputs and calculates the results.
5. The WTF operator receives an e-mail alert with the RCM water quantity value calculated by the data-housing software.
6. The WTF operator adjusts the water release valve to deliver the water quantity calculated by the data-housing software.
7. The WTF operator records the valve adjustment in a log book.

18.7.5 Monitoring and Reporting

An extensive monitoring and reporting program will be administered for this project. Figure 18.6 provides an overview of the monitoring and reporting elements.

18.7.6 Mapping and Land Use/Crop Status Inventories

The project requires verification of planting status (planted or fallow), crop type, and, if deemed necessary, growth vigor of the agricultural stand (quantified and documented). Landsat satellite imagery (approximately 30-meter resolution) will be obtained twice a year to confirm and supplement field verification activities. The timing of imagery acquisition will likely be during the summer (after all fields have been planted) and in the winter to capture winter crops that have been planted between main season crops when the land is typically left fallow.

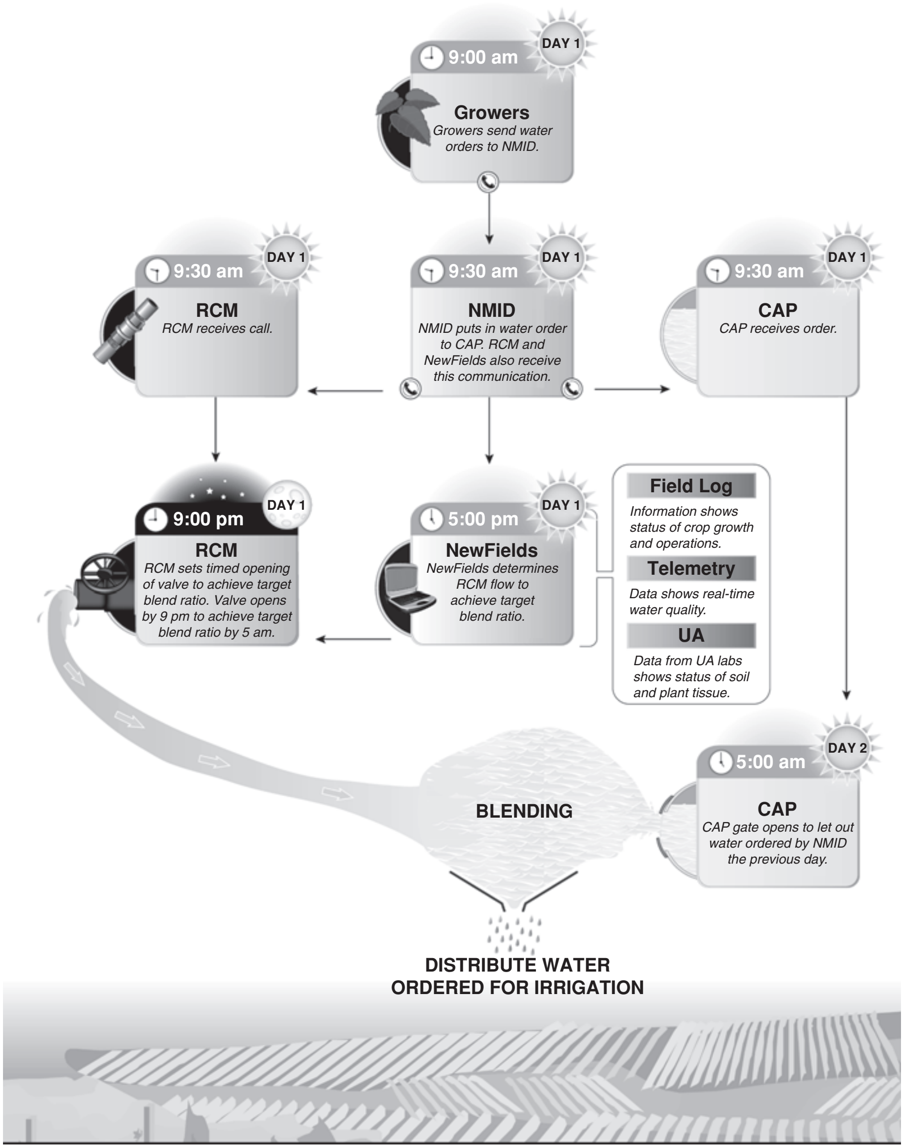

FIGURE 18.5

Overview of blending protocol.

Type of Monitoring	Sampling Frequency	Reporting Frequency
Water		
Continuous	Daily (hourly basis)	Weekly, monthly
Manual sampling	Monthly/Quarterly	Quarterly
Soil		
Continuous	Daily (hourly basis)	Weekly, monthly
Plant Tissue		
Manual sampling	Periodic/Quarterly	Quarterly
Field Operations/Crop Status		
Manual field log	Weekly	Quarterly
Land Use Mapping		
Satellite imagery	Quarterly	Quarterly

Notes: All data will also be included in annual reports. Background sampling and reporting is not included in this table.

FIGURE 18.6

Overview of monitoring and reporting plan.

All imagery will be used to maintain accurate field data (soil type, crop type, planting date, fertilizer applications, etc.) for each field receiving blended water. It will be archived for continued use throughout the project.

18.7.7 Sampling and Analysis

The purpose of the sampling and analysis plan (SAP) is to ensure that the quality of the blended water does not adversely affect crop growth, yields, or soil conditions. This will be accomplished through monitoring of the following:

- Water quantity and quality
- Soil chemical and physical properties
- Plant tissue chemical composition and crop yield

Background levels of nutrients and metals will be established in all sample types before irrigation with the blended RCM/CAP water. Regular monitoring of water, soil, plant tissue, and yield will ensure that soil and crop productivity remain relatively unchanged throughout the duration of the project.

Land Use Assessment

In April 2007, a land use assessment was conducted for the NIMDD C-system to delineate currently irrigated areas (Figure 18.7) and crop types. It will be necessary to conduct this twice a year for soil and crop sampling purposes and to record what crop type has been and is being grown in specific fields. There are direct correlations between crop type and nutrient uptake as well as sensitivities to salts and other constituents.

As of April 2007, alfalfa made up approximately 2,224 acres; cotton, 1,920 acres; and turf, 411 acres, for a total of approximately 4,500 acres of irrigated land. The turf areas include a large sod farm near the middle of the C-system, as well as an 18-hole golf course of approximately 80 acres that has several sources of irrigation water. Blended water will be one of those sources.

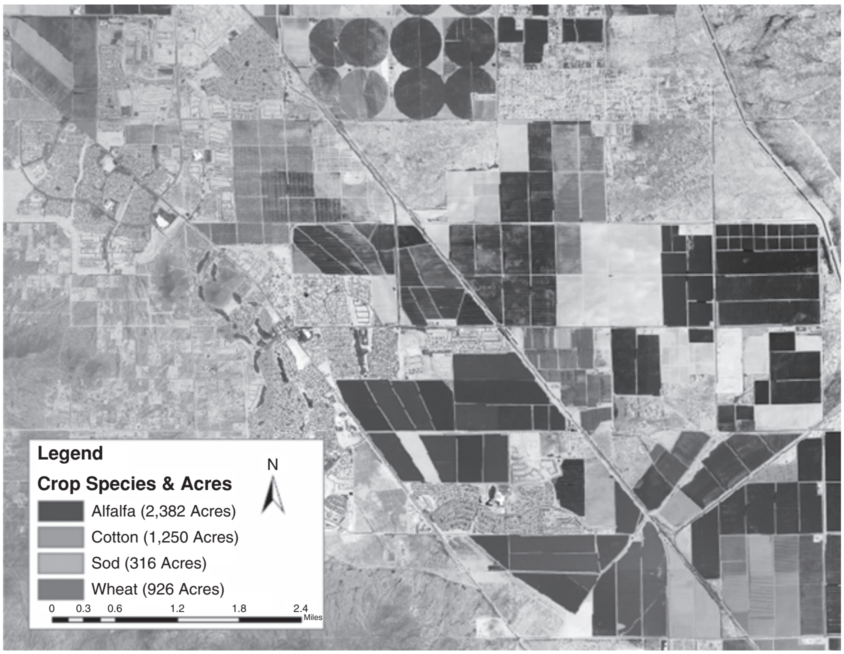

FIGURE 18.7

Irrigated fields and crop types in the C-system of NMIDD (as of April 2007).

18.7.8 Water Sampling and Analysis

Both quantity and quality of blended RCM/CAP water will be monitored frequently. Water quantity monitoring is essential to provide an accurate blending ratio based on the water quality monitoring results. The flow of both water sources needs to be known and tracked to ensure acceptable levels of total dissolved solids (TDS) and other constituents of concern.

Constituents and Schedule

The constituents that will be tested for in the irrigation water are listed in Figures 18.8(a) and (b), which also provide pilot study constituent values, historic CAP values, and approximate 30-day averages for 1:10 blended water. The pilot study data helped to establish working project values. Threshold values for these constituents were also provided and determined according to the limits of irrigation water quality for cotton, alfalfa, wheat, sorghum, and turf. It should be noted that, as the SAP develops, it may be suitable to remove certain constituents of concern from this list or, at a minimum, to reduce the sampling frequency. This will be determined after a series of sampling events.

Water Quantity

The quantity of treated RCM water will be monitored by RCM via flow measurements taken at two different locations. These efforts will be conducted using a real-time, continuous, inline flow meter at the downstream end of the RCM WTF in Superior, Arizona, and at the outfall point into the NMIDD C-system main canal. Resolution Copper Mining will also obtain real-time water quantity data from the turnout of CAP to the NMIDD C-system main canal to ensure accurate blending. The schedule for these data acquisition efforts will be continuous (likely hourly). Data will be stored in an electronic database, reported on an hourly basis, and made available to all project cooperators.

Water Quality

The quality of the water will be sampled in the following three sampling sequences (Figure 18.9, see page 384):

Background. The purpose of the background sampling event is twofold. First, it will ensure adequate water quality at project start-up. Second, it will provide a baseline for comparison of constituent levels with future sampling events. Prior to blending start-up, all water quality parameters will be sampled in both CAP and RCM water in one sample collection event. The analytical results will be summarized in databases that will be available to project cooperators. In addition, it will be possible to identify the source of any potentially elevated constituent levels by individually sampling the CAP and RCM water prior to blending.

Constituents Sampled Monthly

Constituent	Treated RCM —Pilot Study	CAP	1:10 Blended 30-Day —Rolling Average a
TDS/EC (mg/L) (continuously)	9.0	8.6	8.6
pH (standard units) (continuously)	6300	676	1037
ECw (dS/m) (continuously)	9.8	1.1	1.45
Sodium (mg/L)	700	100	127
Calcium (mg/L)	425	78	116
Magnesium (mg/L)	360	30	50.00
Sulfate (mg/L)	4500	207	506
Chloride (mg/L)	20	143	133
SAR (unitless)	5.6	2.7	3.23
Manganese (mg/L)	2.5	.07	0.16
Total Alkalinity (as $CaCO_3$) (mg/L)	33	126	117

FIGURE 18.8(a)

Water quality for treated RCM, CAP, 1:10 blended CAP/RCM water, and threshold limits.

Continuous. Automated, continuous sampling will occur for water quality constituents of EC, pH, and temperature using multi-parameter sensors connected to a data logger.

Routine (monthly/quarterly). Monthly and eventually quarterly sampling events will occur for dissolved metals—monthly during an initial period, and quarterly after sufficient data has been collected to show that the telemetry system is providing accurate data.

Constituents Sampled Quarterly

Constituent	Treated RCM —Pilot Study	CAP	1:10 Blended 30-Day —Rolling Average a
Aluminum (mg/L)	0.100	0.001	0.011
Arsenic (mg/L)	0.015	0.0024	0.003
Barium (mg/L)	0.025	0.094	0.088
Beryllium (mg/L)	0.004	N/A	N/A
Cadmium (mg/L)	0.005	0.005	0.005
Cobalt (mg/L)	0.060	N/A	N/A
Chromium (mg/L)	0.010	0.0061	0.006
Copper (mg/L)	0.010	0.053	0.049
Iron (mg/L)	0.100	2.8	2.557
Mercury (mg/L)	0.0001	0.0002	0.000
Nickel (mg/L)	0.020	0.02	0.022
Lead (mg/L)	0.005	0.00058	0.002
Antimony (mg/L)	0.005	N/A	N/A
Selenium (mg/L)	0.020	0.005	0.006
Thallium (mg/L)	0.050	N/A	N/A
Vanadium (mg/L)	0.025	0.002	0.004
Zinc (mg/L)	0.020	0.002	0.004

*The 30-day rolling average represents the approximate value for a constituent that is expected after continuous water application for an extended period of time (30 days). Values may deviate slightly from the listed value.

FIGURE 18.8(b)

Constituent	Units	Sampling Event
pH	Standard Units	Background, Continuous
TDS/EC	mg/L or dS/m	Background, Continuous
Temperature	°C	Background, Continuous
Sodium	mg/L	Background, Routine
Calcium	mg/L	Background, Routine
Magnesium	mg/L	Background, Routine
Sulfate	mg/L	Background, Routine
Chloride	mg/L	Background, Routine
Manganese	mg/L	Background, Routine
Total Alkalinity (as $CaCO_3$)	mg/L	Background, Routine
Sodium Adsorption Ratio (calculated)	Unitless	Background, Routine
Dissolved Metals	mg/L	Background, Quarterly only

Note: Routine sampling refers to monthly sampling frequency during the initial period, followed by quarterly sampling.

FIGURE 18.9

Constituents for background and routine water sampling events.

An in situ multi-parameter water quality sensor and data logger that measures salinity (EC), pH, and temperature will be installed at the end of the pipeline and within the NMIDD CAP canal both upstream and downstream of the pumping station to allow for real-time monitoring of EC levels. These automatic sampling devices will ensure timely adjustments of blending ratios for adequate water quality.

18.8 DATA INTERPRETATION AND REPORTING

The critical element in project success is the provision of usable data to decision makers across multiple entities. The management and flow of information are specifically targeted to achieving data fluency. This data fluency will be the basis for ensuring the proper functioning of feedback mechanisms for testing and adjusting the system. To achieve this, data will be maintained on a user-friendly Web Data Center Web site accessible to all stakeholders on an ongoing basis. All results will be analyzed for trends using statistical analysis appropriate to the sampling methodology.

18.9 CONCLUSION

This case study illustrates the capacity to work cooperatively to conserve water, the most precious resource in the desert. The foundation of this cooperative effort is a robust system for collecting, analyzing, and responding to changing data.

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CHAPTER

Greenhouse Gas Assessment at Barksdale Air Force Base—A Case Study

19

Mica Heilmann, Stephanie Tillman

19.1 INTRODUCTION

In 2008, the United States Air Force (USAF) initiated a directive to offset fund reductions by developing a better understanding of natural infrastructure assets to achieve optimum resource efficiency. Air Combat Command Asset Management requested an analysis of the equity of built and natural resources for Barksdale Air Force Base (Base) in Louisiana to develop a Sustainable Asset Accounting System, which is much like a corporate balance sheet (for further discussion, see Chapter 25).

One part of the balance sheet involved estimating the carbon value associated with natural assets in Base landholdings. The objective was to improve the natural resource data inventory and potentially use this data to manage natural resources more efficiently on the Base and, possibly, on other bases. This involved evaluating and quantifying the spatially related greenhouse gas (GHG) flux values for the Base to determine if these areas are GHG sources (emitting) or sinks (sequestering). An important aspect of this evaluation was to determine the change in GHG flux over time, which is influenced not only by weather but also by changes in land cover and/or land use. This case study describes the background, assumptions, methodology, and results of developing a spatially related estimate of GHG flux for the Base.

19.2 BACKGROUND

The Base covers an area of approximately 22,000 acres in northwestern Louisiana, near the cities of Bossier and Shreveport. Most of it (approximately 18,000 acres) is covered in lowland and upland forest, including coniferous, mixed, and hardwood stands. A small portion (approximately 1,200 acres) is considered wetlands. Greenhouse gas flux is expected to vary with these land cover classes. The following are the main GHGs that contribute to global climate change:

- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)

DOI: 10.1016/B978-1-85617-797-9.00019-8

Carbon flows between soil and the atmosphere through the paired processes of photosynthesis and respiration. *Photosynthesis* is the process by which plants fix CO_2 from the atmosphere into carbohydrates, which can then be converted to plant structural components or other necessary compounds. These carbon compounds enter the soil when plants die or shed litter or through the process of root exudation. Once in the soil, carbon is primarily stored as soil organic matter. Some of it is then converted to new carbon compounds by soil microorganisms. These compounds can become either physically or chemically stabilized and thereby sequestered from the atmosphere in the form of soil organic carbon.

The main sources of CH_4 are natural areas, flooded rice, ruminants, wetlands, and lagoons. Saturated conditions, such as those found in wetlands, create the conditions for CH_4 production. Major sources of N_2O include natural systems, agricultural soils, and deforestation and clear cutting. The global budget for N_2O is the least well known.

Although CO_2 is by far the main GHG by volume, the global warming potentials of CH_4 and N_2O are 25 and 310 times greater, respectively, than that of CO_2. Therefore, all three GHGs should be considered in determining GHG flux. The flux of GHGs other than CO_2 is expressed as CO_2 equivalents because CO_2 is the GHG recognized in climate exchange markets, as explained in the next subsection.

The objectives of the GHG exchange quantification for the Base were as follows:

- Using satellite imagery taken on September 28, 2001; April 1, 2005; and March 22, 2008, develop representative land cover classifications to serve as input for simulating the spatial and temporal variation of GHG flux.
- Determine the most accurate method of quantifying GHG flux for a given site.
- Investigate the methodologies that are accepted by the Chicago and European climate exchanges for validating carbon offset projects.
- Choose a methodology to quantify GHG flux that can take into account the various land cover classifications on the Base, is scientifically rigorous, and has potential for acceptance on the climate exchange markets.
- Determine spatial and temporal GHG flux variation on the Base.

19.2.1 Carbon Accounting and Exchanges

The policy tool that has been developed in the United States to reduce GHG sources (which focuses on CO_2 because it is the most significant GHG by volume) is known as a cap-and-trade system, whereby carbon-producing industries voluntarily commit to reducing the amount of CO_2 they produce—their "carbon footprint"—to below a specified cap or upper limit. If an entity exceeds this cap, carbon credits can be bought from another entity that produces carbon sources in amounts below it. Conversely, entities that can prove they have sequestered carbon through management alternatives may sell carbon credits to emitters. For this reason, commodity exchanges that trade "carbon credits" and other pollutants have developed.

There are four main carbon exchanges currently operating in the world: the Chicago Climate Exchange, the European Climate Exchange, the Montreal Climate Exchange, and the Tianjin Climate Exchange. For this project, the Chicago Climate Exchange (CCX) and the European Climate Exchange (ECX) were investigated.

19.2.2 The Chicago Climate Exchange

The CCX was launched in 2003 and is North America's only active system for registering GHG offsets, reducing GHG emissions, and trading GHG credits. It is a member-based exchange that also includes offset providers or aggregators. Members are direct emitters of GHGs that make a voluntary but legally binding commitment to the CCX Emission Reduction Schedule, in accordance with which they are allocated annual emission allowances. Offset providers or aggregators are owners or groups of qualifying mitigation or offset projects that store, destroy, or reduce GHG emissions.

The CCX's tradable instrument is the carbon financial instrument (CFI), which represents 100 metric tons of exchange allowances or exchange offsets. Members who reduce GHG emissions below their targets may sell their surplus allowances or bank them for future use. Members who do not meet the targets must comply by purchasing CFI contracts.

The Chicago Climate Futures Exchange (CCFE) is a wholly owned subsidiary of CCX that offers futures and options contracts on emission allowances. As of November 2008, the CCX had traded 67.3 million metric tons of CO_2. This represents 672,611 CFI contracts. During 2008, prices ranged between $1.00 and $1.55 per metric ton of CO_2 across all vintages.

Eligible forestry offset projects that can be used for emission reductions and sequestration, and therefore used in a CFI contract, include afforestation, managed forestry, carbon storage in long-lived wood products, emission reduction through deforestation and degradation, and urban tree planting.

All projects are subject to third-party verification by a CCX-approved forestry verifier. In order for offsets to be issued, net growth in forest carbon stocks must be quantified using one of the CCX-approved quantification techniques. These techniques include approved biophysical growth and yield modeling.

19.2.3 The European Climate Exchange

The ECX also operates under a cap-and-trade system, though its scope is international. The European Union Allowance (EUA) is the commodity traded as either a futures or an options contract. EUAs are equivalent to the right to emit one metric ton of CO_2 and are issued by the Emissions Trading Scheme (ETS), which is a multi-country emissions-trading system. CFI contracts are used on the ECX as well and represent 1,000 EUAs. The ETS operates in phases, where phase I corresponds to the years 2005 to 2007; phase II, 2008 to 2012; and phase III, 2013 to 2020. During 2008, prices ranged between €10 and €20 per metric ton of carbon across all vintages.

The “EU Emissions Trading Directive 2003/87/EC,” also known as the Linking Directive, provides specifications on offset projects; however, this information is far less detailed than that provided by the CCX.

19.3 ESTIMATING GREENHOUSE GAS FLUX AND THE DNDC MODEL

Several methods for estimating greenhouse gas flux were investigated in order to select the most appropriate for Base analysis. Several factors were considered, including accuracy, availability, applicability to range of site conditions, and acceptability to the Chicago and European climate exchanges for validating offset projects.

19.3.1 Estimating Greenhouse Gas Flux

Terrestrial carbon pools (especially in forests) are highly spatially heterogeneous and dynamic, and pose challenges in quantifying terrestrial carbon inventories and fluxes. According to Birdsey (2006), forest carbon balance may be assessed using one of three methods:

- Lookup tables
- Direct or indirect measurement of CO_2 exchange
- Modeling

Lookup Tables

Lookup tables include values of carbon exchange for different vegetation from various sites that represent a region. These values have been obtained through scientific study and documented in the literature. Though this is likely the quickest way to estimate a forest carbon budget, it is the least desirable because it is not site specific. Examples of lookup tables are the 1605B carbon inventory tables published by the USDA Forest Service. These are helpful in converting stand productivity and biomass to carbon mass, and they form the database for the Carbon Online Estimator (COLE), which may be used to quickly estimate carbon sequestered in various forest types in the United States.

Another source of carbon sequestration values for forests is the Southern Online Estimator (SOLE), a more specific version of COLE. Although this tool is based on lookup tables, it allows the user to choose fairly specific variables, such as stand size, origin, and age class; disturbance; forest/species type; site productivity; and physiographic region and ecological section. Like COLE, SOLE’s main limitation is that the information on which it is based often consists of measurements taken from a small number of sites within a region.

Measurement

Carbon status may be determined using instruments that measure carbon exchange within an ecosystem and result in a measure of net ecosystem exchange

(NEE). Though this method likely provides the best results, it is time consuming and expensive and, because of temporal variability, is valid only for the time period of measurement. Unlike lookup tables, this method is site specific and regional estimates must be extrapolated from it. Therefore, it is not an appropriate method for large areas, though it does provide a good point of comparison when site-specific evaluations of carbon flux are estimated, and it is extremely useful for model calibration and validation.

Modeling

Models have the following advantages for estimating the carbon balance of an ecosystem:

- They simplify complex systems.
- They can synthesize data to integrate several processes that occur simultaneously in one system.
- They are useful for testing hypotheses.
- They may be used as prediction tools.

Modeling has been determined to be the most practical method of quantifying GHG flux from large, complex sites, and it is the only practical, site-specific method accepted by climate exchanges. Literature values are limited and not site specific, and direct measurement is time consuming and costly.

Several biogeochemical models have emerged in the last 20 years to estimate carbon flux and ecosystem production. Tretten and colleagues (2001) reviewed 12 carbon models and found that most of them had the following drawbacks:

- They do not account for anaerobic conditions.
- They do not explicitly simulate wetland hydrology.
- They cannot track daily biogeochemical dynamics.

The DeNitrification–DeComposition (DNDC) model was developed, in part, in response to these shortcomings. This model is considered the best quantification tool currently available because it considers all major greenhouse gases and has a superior method of modeling wetlands, which are a distinct land cover class on the Base. It can also be applied to agricultural lands and forested uplands. The model has been verified over several landscapes across the United States and is likely the most appropriate tool for nationwide use.

19.3.2 Denitrification–Decomposition Model

The DNDC model was selected for Base greenhouse gas flux analysis. Wetland/Forest-DNDC is a modified version of the Photosynthesis and Evaporation-Nitrogen (PnET-N) DNDC model originally designed for simulating carbon and nitrogen dynamics in upland forest ecosystems.

The DNDC model had the following advantages for the Base analysis:

- It considers Base forest and wetland assets.
- It takes into account site-specific characteristics, including soils, vegetation, groundwater conditions, and the like.
- It considers multiple greenhouse gas sources.
- It has been broadly verified.
- It can simulate the impact of silvicultural management practices on net GHG emissions.

These combined characteristics were needed to accurately assess Base resources and will be needed for ultimate asset verification by climate exchanges. Simpler models and empirical methods do not provide the level of accuracy needed for verification on a climate exchange.

Forest-DNDC is a process-based, biogeochemical model that simulates forest photosynthesis, respiration, carbon allocation, litter production, turnover of soil organic matter, trace gas emissions, and nitrogen leaching. It runs at a daily time step and produces daily and annual results of forest growth; net ecosystem carbon exchange; and fluxes of CO_2, CH_4, N_2O, N_2, and NH_3 emissions. The model has been validated at site and regional scales in North America, Europe, and Asia. A partial list of the literature documenting these validation studies can be found at the Global DNDC Network (*www.globaldndc.net*) or at the model's Web site (*www.dndc.sr.unh.edu*).

Forest-DNDC has four components:

- Hydrological conditions
- Soil temperature
- Plant growth
- Soil carbon and nitrogen dynamics

The processes of these four components interact closely with one another. Model inputs include daily meteorological data; forest type, age, and management; soil properties; and water table positions and dynamics (for wetland simulations). Model outputs include carbon pools and fluxes, nitrogen pools and fluxes, and thermal/hydrological conditions.

DNDC may be used at a site or regional scale. The site model allows the user to input specific ecological characteristics that apply to the entire site. The regional model allows the user to divide an area into cells or polygons, using GIS to apply different attributes to each one. The model then outputs results for the region by cell.

Methodology

For this analysis, the DNDC model was run on the primary forested portion of the Base (17,600 acres), which was determined to represent the greatest potential sink for greenhouse gases. However, the developed portion of the Base could also be modeled. Of the area excluded from the model, approximately 1,500 acres were determined to be impervious. Physically, impervious areas are considered to have a null greenhouse gas flux value and therefore are not of great interest for this type of assessment. The remaining areas that could be assessed included irrigated landscape areas, recreational areas, and nonirrigated open spaces.

The following subsections outline the data required for the DNDC model and the data sources and assumptions used for the analysis of Base greenhouse gas flux. It should be noted that, although the DNDC model provides far greater accuracy and confidence in greenhouse gas assessment than empirical methods, it has specific data needs. Some of the data it requires were not readily available for the Base, and therefore regional values or assumptions were used.

The minimum inputs required for the regional (landscape scale) DNDC model are summarized in Figure 19.1. Most of them were available; however, two important ones were lacking or not sufficiently detailed: water table position and initial biomass. For these inputs, reasonable assumptions were obtained from other regionally applicable data sources.

Selection of Grid Cells for Modeling at a Landscape Scale

Grid cells represent the spatial granularity of the model input, analysis, and output flux values. Because GHG flux values are calculated for each grid cell's data, it is important to determine appropriate granularity and physiographic commonality to determine the grid cell delineations based on the modeling objectives. Key data considered in establishing the modeling grid included:

Satellite imagery of the Base. This was obtained from three dates (in 2001, 2005, and 2008) to capture major changes in land cover class and infer major management practices. A complete object-based land cover classification was performed on the 2005 imagery. The classification scheme included impervious surfaces, open water, grassland/herbaceous, coniferous forest, deciduous forest, mixed forest, bare rock/soil, woody wetlands, and emergent wetlands.

Base soil types. These corresponded to physiographic regions on a large scale, and would likely correspond to vegetation types on a more refined scale. Soil properties that influence greenhouse gas flux (those required by the model as listed earlier) likely vary with soil type and therefore would probably also vary with vegetation.

Base forest management. Three forest management classes are used on the Base: commercial forest, modified commercial forest, and noncommercial forest. With the exception of natural areas (unmanaged), management corresponded to land cover class because various vegetation types are managed differently.

Base hydrological data. Hydrological data was limited. Water table levels and dynamics were represented by minimum water table depths associated with soil types.

Input	Data
Climate	Daily precipitation and minimum and maximum temperatures
Soils	Bulk density, pH, texture, organic C content, stone fraction, obtained from USDA NRCS
Vegetation	Daily precipitation species, age of stand, initial biomass, minimum and maximum temperatures
Management	Daily frequency and amount of harvesting, prescribed burning, thinning, draining, fertilizing, planting, upper-story harvesting, under-story chopping, and minimum and maximum temperatures
Hydrology	Daily water table elevation. Greenhouse gas flux is highly dependent on water status of soils and is particularly important in wetland areas. Data with this level of detail are rarely available; therefore, water table dynamics are often modeled if actual observations are not available.

FIGURE 19.1

DNDC model input requirements. Greenhouse gas exchange quantification for Barksdale Air Force Base, Louisiana.

From the available data, soil types and management were the main considerations for developing grid cells for the regional model run.

Forest Management

Commercial forest on the base corresponds approximately to the pine uplands and is managed as an even-aged stand on a 100-year rotation. Since there are approximately 8,000 to 9,000 acres of pine uplands, approximately 1 percent (80 acres) is harvested each year and immediately replanted. To manage where the harvesting takes place in any given year, the pine uplands are divided into seven compartments, which are on a regular cutting cycle. Each year, cutting takes place in only one compartment, so stands from each compartment are cut only once every seven years (Barksdale AFB Second Bomb Wing, 2007).

Modified commercial forest refers mainly to hardwoods (bottomland and upland). These are not managed on a regular rotation; however, various silvicultural management practices are used to maintain optimum forest health as necessary. Noncommercial forest comprises natural vegetative areas that are not managed in any way and urban tree stands and recreational areas. Fertilizing and draining are currently not used on the Base forest.

Results

The 17,600 acres of forested and wetland area modeled represented a considerable asset with respect to greenhouse gas sequestration. Figure 19.2 shows the total gas flux of the modeled gasses carbon, N_2O, and CH_4, as well as the total of the greenhouse gases, shown in CO_2 equivalents for the modeled Base area. Negative values indicate greenhouse gas sequestration. Positive values indicate emissions. Figure 19.3 shows the entire area of the Base that was modeled and the resultant totals for GHG flux.

The DNDC model was run separately for wetland and upland areas to account for distinctly different characteristics. Combined results indicate that Base forests and wetlands sequester 46,128 metric tons of greenhouse gas (CO_2 equivalents) on average per year. At a rate of $1.50 per metric ton on the Chicago Climate Exchange, this equates to a value of nearly $70,000 annually.

As shown in Figure 19.4, assessment of greenhouse gas flux per unit area of forest class indicates the difference in sequestration achieved by the various forest ecosystems. On a per-acre basis, coniferous forest on the Base sequesters approximately 58 percent of the greenhouse gas that the deciduous forest sequesters. It should also be noted that sequestration achieved by commercially managed forests is offset to some degree by emissions resulting from the forest harvest process. Base management for commercially managed pine includes harvest of approximately 80 acres of forest area per year. This forest area is

	Uplands	Wetlands	Total
Hectares Modeled	6,507.8	473.6	6,981.4
Greenhouse Gas (GHG)	Average Annual Flux (kg/yr)1		
C	−11,976,115	−1,006,861	−12,982,976
N20-N	3,084.1	135.9	3,220
CH4-C	−3,387.3	96.6	−3,291
Total GHG (CO_2 equivalents)	**−42,504,851**	**−3,622,929**	**−46,127,781**

FIGURE 19.2

Average annual greenhouse gas flux. Greenhouse gas exchange quantification for Barksdale Air Force Base, Louisiana.

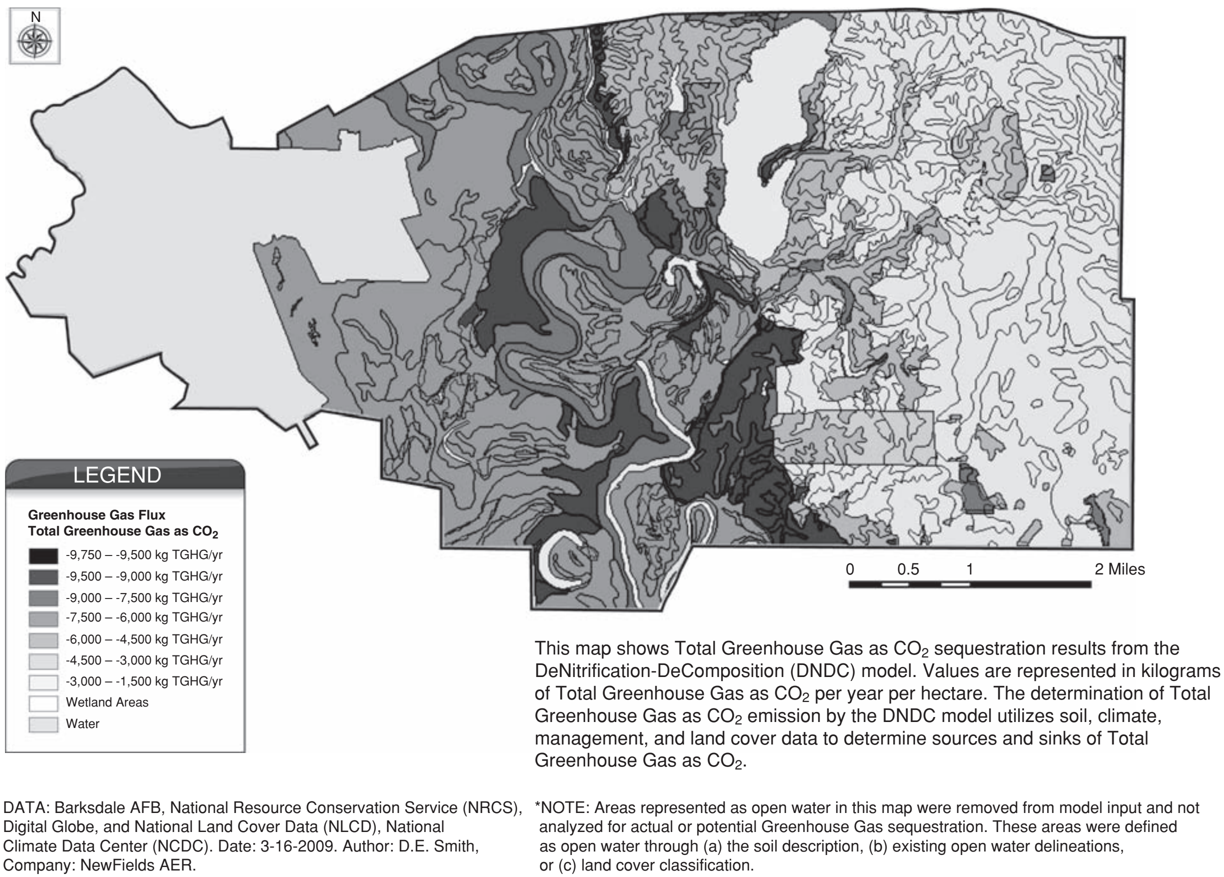
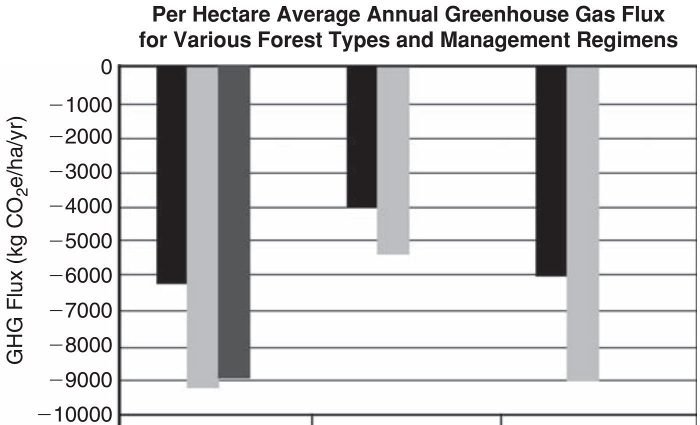


FIGURE 19.3

Fluctuations in total greenhouse gas as CO_2 sequestration across Barksdale Air Force Base.



	Deciduous	Coniferous	Mixed
Commercial	−6163.2	−3980.7	−5956.5
Noncommercial	−9125.2	−5327.9	−9033.2
Modified Commercial	−8864.9		
Average	−8051.1	−4654.3	−7494.9

FIGURE 19.4

Greenhouse gas sequestration was highest in deciduous forest areas. The managed (commercial) forest showed less overall sequestration than the unmanaged (noncommercial) forest.

managed on an approximate 100-year rotation. Given an average age of 90 years for harvested forest, the modeled biomass removed during harvest would be approximately 4,597 metric tons of carbon. A portion of this carbon is emitted through lumber processing and waste, and a portion remains sequestered through long-term end use.

The California Climate Action Registry Protocol (CCAP) provides a method for estimating 100-year persistence of wood product carbon. The method uses assumptions for mill efficiency in converting harvest trees to lumber and for the percentage of remaining wood product in use and landfills after 100 years. Under these assumptions, a little over half, or 2,832 metric tons, of harvested carbon is lost as emissions over the 100-year period, equating to 10,383 metric tons of CO_2 equivalent (CO_2e) emissions.

Because forests on the Base are consistently managed, this approximate emission of CO_2e can be assumed annually. For comparison, 80 acres of commercial pine sequesters approximately 129 metric tons of CO_2e per year, and the entire east reservation forest area sequesters 46,128 t CO_2e/yr. Roughly, then, 23 percent of forest sequestration is lost to harvest-related emissions (67 percent of just commercially managed forest sequestration). Nevertheless, the Base's forest-harvesting practices are integral to the current age distribution and management of its commercial forest, and they also positively influence overall biomass production.

The following values summarize the GHG fates in units of CO_2 equivalents:

- Total annual forest GHG sequestration (t CO_2e/yr): 46,128
- Total annual commercial forest sequestration (t CO_2e/yr): 15,509
- Annual harvest (80-acre) GHG emissions (t CO_2e/yr): 10,383

19.4 CONCLUSIONS AND RECOMMENDATIONS

The following points summarize the conclusions and recommendations resulting from analysis of this case study:

- Though CO_2 is by far the main greenhouse gas by volume, the radiative effects of global warming potentials for CH_4 and N_2O are 25 and 310 times greater than CO_2, respectively. Therefore, all three greenhouse gases should be considered in determining greenhouse gas flux.
- Simple models and empirical methods do not provide the level of accuracy needed for verification on a climate exchange.
- The DNDC model was selected because it considers the three greenhouse gasses and evaluates agricultural, forest, and wetland areas and their site-specific conditions. As a result of this exploratory effort, this model will be recommended for future refined assessments or for expanded modeling.
- Observed and modeled biomass values for the modeled Base area compared well, indicating that the DNDC model performed well in capturing forest growth in Base forest areas.
- High-resolution image assessment results were detailed compared to the level of detail required for DNDC model input. Combined (less detailed) satellite image land cover classes compared favorably with the level of detail in national land cover data sets (available for 1992, 2001, 2006). This indicates that these publicly available data can be used instead of custom image analysis, resulting in significant cost and time savings, especially if multiple sites are to be compared across a broad geographical area. Some lower-level image review is recommended to verify land cover information and to refine assumptions on land management where needed.
- Most of the data required for the DNDC model inputs were available from Base or public sources; however, two important types of data—water table dynamics and initial biomass—were lacking or not sufficiently detailed. Although modeling assumptions were made to allow completion of modeling tasks, collection of some refined data is recommended as needed in future applications. These data will probably be needed to develop modeling results robust enough for

third-party verification on a climate exchange. Specific data collection needs that will likely arise in future assessments include the following:

1. More detailed groundwater observations across different land cover classes (by piezometer or other comparable approach).
2. Initial biomass estimates based on field observations.
3. Forest age assessments based on field observations.
4. Wetland depth and inundated area information based on field observations.

- An additional step in model output analysis is to identify land management refinements that could maximize total greenhouse gas sequestration. Identifying such refinements is a natural and fairly simple next step in the analysis and will provide for true optimization of Base assets and asset value. For example, a shift in fire frequency or rotation length of forest stands can have a significant impact on net GHG balance and resultant sequestration.
- Developed/urban areas should be modeled in some circumstances, given additional information or data on specific management practices for dominant urban uses. Although modeling of every landscaped or vegetated area may be excessive relative to the value obtained, assessment of prevalent uses such as golf courses, recreational areas, and airfield buffer areas may be worthwhile. However, it is advisable to look more closely at existing contracts on climate exchanges to determine what precedent has been set with regard to these smaller and much more variable sources before investing in detailed quantifications.

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PART

Introduction to Decision Implementation IV

Kandi Brown

The previous parts of this book focused on the regulatory framework in which we operate, the use of Decision Consequence Analysis (DCA) to quantify the impact of our decisions, and the tools that provide the foundation for DCA. This part examines how decision making is ultimately a people process. Appropriate stakeholders must be identified and engaged, groups must coalesce around binding agreements on future actions (while being guided to maintain strategy in the long term), and decision-making momentum must be achieved. In most situations, the strategy of the group must be enforced through negotiation and oversight of effective, meaningful contracts.

Delivering a technical message to a nontechnical audience, promoting consensus among diverse stakeholders, managing data to the highest degree of quality standards available, and executing work in the most efficient and effective way possible are highlighted in case study formats presented in each chapter. Chapter 20 addresses the issue of defining stakeholders and key decision makers in large groups. Chapter 21 explores a case history demonstrating streamlining of a large group of decision makers to a DCA team functioning in a facilitated session. Chapter 22 provides a road map on how to improve the efficiency of well-established partnering teams through the use of decision metrics. Chapter 23 moves beyond the use of facilitation techniques to garner binding agreements to the use of contractual mechanisms to support implementation.

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CHAPTER

Sustainable Diverse Stakeholder Engagement

20

Adam Saslow, Kandi Brown

Since the passage of the first environmental statutes in the late 1960s and early 1970s, federal and state agencies have largely relied on a "command and control" legal structure for achieving environmental gains. In this structure, regulators seek to control environmental damage by telling facilities how they must design and manage processes that may generate pollution. The paradigm for environmental protection began to shift in the early 1990s as the Clinton Administration explored regulatory negotiations as well as innovative voluntary programs designed to encourage superior environmental performance through tangible and intangible incentives. The Environmental Leadership Program, the Common Sense Initiative, Design for the Environment, Energy Star, and Performance Track have all advanced the thinking and practice for "beyond compliance" performance at the federal level.

The state of the art has evolved over nearly twenty years and has touched every sector of the economy. Programs have improved not only because of the lessons learned by government but because, in almost each and every case, program design has been informed by collaborative dialogue that brings stakeholders together in a safe environment. During the last twenty years, many forms of collaboration have been used to resolve disputes and create cultures of environmental stewardship in every corner of the country and across the full range of environmental issues.

20.1 THE COLLABORATIVE CONTINUUM

Collaborative problem solving may not be appropriate for every environmental issue. It is important to recognize the times for its proper application as well as the many process models available. Collaborative dialogue can take many forms—each with its own idiosyncratic rules of engagement and nuance. Following is a list of forms of collaborative dialogue:

Independent action. One party acts of its own accord and, if acting rationally, takes steps toward some desired positive net benefit.

Partnering. A small group of stakeholders (partners) gather that are directly and unequivocally impacted by the outcomes of a given discussion. Each partner is

DOI: 10.1016/B978-1-85617-797-9.00020-4

asked to contribute to a larger goal and, in doing so, directly contributes to progress. Partners receive primary (not secondary or tertiary) benefits and improve their standing as the course of events unfolds. Partnering efforts may or may not be designed and guided by a neutral third party.

Traditional facilitated dialogue (TFD). Multiple stakeholders gather to discuss a bounded set of issues and resolve those issues based on a predetermined decision rule. A neutral process guide identifies the points of conflict, develops a road map, and structures conversations in a safe environment so that the stakeholder group reaches decisions in a manner that maximizes comparative advantages. Participation in the process is expanded or contracted as suggested by a "conflict assessment." Agreements are memorialized by signature or other form of endorsement before the dialogue is concluded.

Decision-based partnering (DBP). An established partnering team focuses on increasing the probability of program completion through use of technical facilitators to help develop and implement decision logic and program management tools. With technical academic backgrounds and experience in advanced program management, technical facilitators function as independent neutral parties working with mature partnering teams to accelerate achievement of program objectives. (See Chapter 22 for a detailed example of DBP.)

Facilitated decision consequence analysis (FacDCA®). A DCA is completed in a facilitated context with continuing involvement by technical facilitators as the DCA action plan is implemented and monitored. (See Chapter 21 for a FacDCA case study.)

Mediation. Similar to partnering, mediation involves a small group of stakeholders who are directly and unequivocally impacted by the outcomes of a given conflict. A neutral third party structures independent and collaborative dialogue in a manner that enables the mediator to propose solutions that may or may not be accepted and endorsed by the stakeholders. The single most important distinction between TFD and mediation is that solutions rise up from the group in TFD; the mediator defines the solution in a mediated process. The solution may or may not be embraced by the affected parties.

Arbitration. Parties agree *a priori* to present their respective cases to a neutral third party and then empower that third party to judge and decide the merits of the presentations. All decision-making power and authority resides with the arbitrator. Parties may or may not be bound by the ultimate decision.

The preceding continuum is notable for more than the definitions themselves. The reader should appreciate that as one moves from individual decision making toward arbitration, less and less power resides with stakeholders. More and more power shifts to some unaffected, neutral third party.

The importance of this shift is both profound and pronounced, and it is most typically realized in the implementation phases of conflict resolution. As participants in collaborative dialogue maintain control of their own destiny, they tend to embrace the tasks associated with advancing stewardship, resolving problems, and productively and constructively addressing conflict. As control over the process is lost, so typically is the energy committed to these tasks. That is not to say that mediation and arbitration do not have a place in the proverbial tool box—they do. Many disputes cannot be resolved via dialogue, and an empowered decision maker may in fact be the only means for resolution. Nevertheless, when one has the opportunity to use collaboration for dispute resolution, the tool chosen must fit the issue. Experience suggests that mediation and arbitration do have attendant costs. For the remainder of this chapter, we will focus on TFD, DBP, and FacDCA.

People often joke that "success" in a TFD, DBP, or FacDCA collaborative process means that everyone is equally unhappy. According to some, participants in these dialogues tend to look at them as a zero sum game: For every winner there is a loser. Sadly, this is often the reality, as the average facilitator is concerned with process over substance, time and not quality. As graphically represented in Figure 20.1, stakeholders are spokes connecting at a facilitation and information hub. At the end of most facilitated processes, they typically range from highly satisfied to highly unsatisfied. We call this the "amoeba model." When the points are connected, the resulting shape looks like an amoeba.

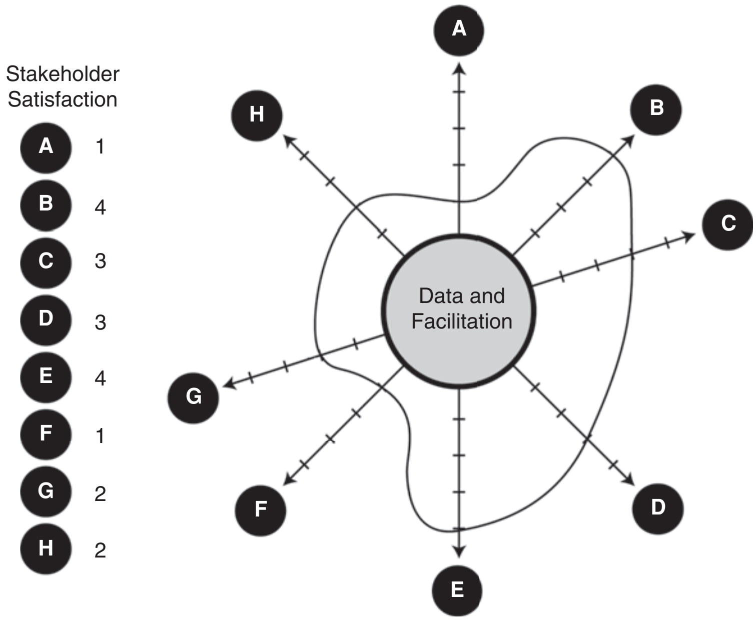

FIGURE 20.1

The amoeba model.

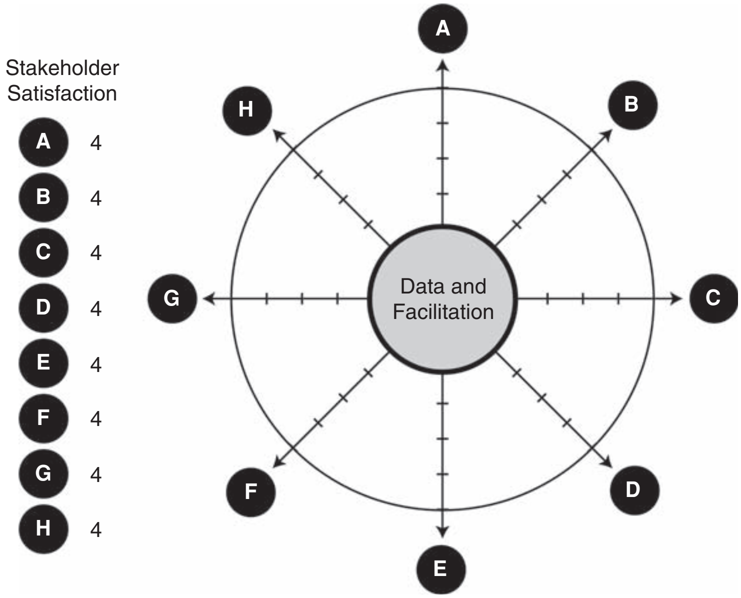

FIGURE 20.2

The wheel model.

In contrast, the best process guides identify comparative values and use them to optimize satisfaction. Before every dialogue, the process guide uses conflict analysis and other techniques to have stakeholders articulate their interests and their objectives. Throughout the dialogue, she nurtures both the stakeholder–facilitator relationships and the stakeholder–stakeholder relationships. Process guides obtain data and create information useful to all participants as they work collaboratively to identify common desirable endpoints. They use science, group dynamics, and psychology to demonstrate the systemic properties of policy. Process guides forge agreements that participants embrace by capitalizing on different values placed on desirable outcomes. We call this the "wheel model" (see Figure 20.2). At the end of a good collaborative process, the result appears as a wheel—perhaps the most important engineering innovation in the history of man—which serves as a metaphor for progress. In the following sections, we discuss several common elements of TFD, DBP, and FacDCA that must be considered.

20.2 PROBLEM IDENTIFICATION

To select the right tool, one must first correctly identify the problem. Collaborative dialogue is not the right "hammer" for every issue. Sometimes decision makers need a "screwdriver." Decision makers must ask several key questions before determining how to proceed:

Question 1. What is the problem? While elegant in its simplicity, this question should require the greatest commitment of time and intellectual capital. Once it is answered, the following questions should be addressed in succession.

Question 2. Can I solve this problem through my own actions, or do I need others to contribute time, energy, or resources?

Question 3. Do I have the power not only to choose from among the solution alternatives but to implement the optimum solution? Can I implement the solution unilaterally?

Question 4. Does the range of solution alternatives impact others to any degree or to varying degrees?

If any of these questions indicate the need to incorporate other parties, it may be worthwhile to consider and ultimately convene some form of collaborative dialogue. Decision makers then become conveners of a collaborative process as they bring together parties to work in a unique space or institution solely to resolve a problem.

Problem structuring based on decision triggers is the foundation of FacDCA. Chapters 5, 6, and 21 provide a thorough discussion of the pitfalls of inaccurate problem formulation during a FacDCA or DCA process.

20.3 PROCESS DESIGN AND CONFLICT ASSESSMENT

Conveners must next decide whether to design and guide a collaborative process from their existing perch or to look to someone else to be the process designer or guide. Often it is necessary to use a trained coach, facilitator, mediator, or arbitrator. The question is one of both skill and the possibility of conflict of interest. Does the convener (or convening organization) have the internal knowledge, skills, and abilities to lead a multi-stakeholder process? Can the identified problem be handled internally without undue conflict of interest?

Most of the time, the answers to these questions suggest that conveners engage a neutral third party. It is rare that the costs associated with a neutral third party outweigh the benefits, as a trained guide can help insulate conveners and make the process more "bulletproof" than if it were to be designed and guided by an internal resource that could possibly benefit from a given outcome.

Whether the process guide is an internal resource or an outside contractor, some form of conflict analysis should be undertaken. The product of this analysis may be known as a conflict assessment, a convening assessment, a conflict analysis, and/or a landscape assessment. Additionally, the technical qualifications of the facilitator or mediator are of the utmost importance. If the team's primary points of conflict arise around issues of soil protection, a technical facilitator well versed in hydraulics will not do. In FacDCA and DBP, technical qualifications and experience are equally weighted with the facilitator skill set.

The process guide begins with a broad characterization of the problem needing resolution. Data are collected that may be pertinent to the parties resolving the issue. The data may come from a variety of sources: published and gray literature, government agencies, geospatial systems, and more. Data collection and information analysis are not simple "check-offs" in the conflict resolution process. They are ongoing throughout the collaborative dialogue. The process guide must sift through reams of data to get the right information to dialogue participants.

During FacDCA and DBP, environmental data are most often gathered into a relational database and a GIS system to rapidly transmit it to all team members to balance power among stakeholders. Real-time analysis of historic trends, remedial approaches, and receptors can take place in a meeting setting using these tools, thereby keeping the decision-making momentum high. The importance of real-time data analysis through GIS and relational databases cannot be overstated. Static maps, tables, graphs, and figures for reports are 19th-century tools that poorly serve decision makers who are attempting to collectively grasp the consequences associated with multidisciplinary sustainability issues.

When working on any project—big or small—there can be hundreds or even thousands of documents to consider. Technical data and information on each regional plan will come from internal and external sources. The process guide must organize all documents, often developing an Internet-based document library to create a Web-based organizational tool and online document database.

To obtain political as well as social/psychological information, process guides complete a conflict assessment at the beginning of nearly all collaborative dialogues. This includes the following steps:

Step 1. Develop an interview guide and conduct interviews with internal and external stakeholders.

Step 2. Use a snowballing process to increase the pool of relevant (though not necessarily legitimate) stakeholders.

Step 3. Gain a complete understanding of the political, economic, technical and other issues impacting the resolution of an issue.

Step 4. Distinguish the legitimate stakeholders from the "wannabes."

Step 5. Review programmatic requirements and program materials to develop an understanding of the context in which collaborative dialogue will take place.

The conflict assessment is often a concrete deliverable. In such cases process guides always sanitize the information to protect the confidentiality of those who share more personalized knowledge and opinions. Occasionally, and in the interests of transparency, the results of the conflict assessment are presented at the opening of a collaborative process.

To summarize, conflict assessment is critical to the credibility of a fair and open process; it ensures that the full range of issues is identified *a priori*; it enhances the quality of the process guide's counsel and strategy; and it highlights needed experts as well as the cross-representation of affected interests.

20.4 INITIATING A COLLABORATIVE DIALOGUE

During the process design and conflict assessment phases, technical information and human elements are combined to present a reasonably complete picture of the issues at hand. The process guide can then define several critical elements of a collaborative process, such as

- The process charter
- Stakeholder group composition
- The road map for dialogue
- Metrics and measures for success

Note that, although many of the preceding elements may be conceptualized and drafted before the collaborative dialogue begins, they must be ratified, endorsed, or approved by the stakeholder group as a general process measure. These process elements are explained in the following subsections.

20.4.1 The Process Charter

The process charter is drawn up prior to any dialogue and is essential to recruitment of participants, the road map's design, the decision methodology, and the ultimate outcomes. Immediately after completing the conflict assessment, the process guide prepares an initial draft of a process charter that specifically defines the issues requiring collaboration and the goals of their resolution. Affected communities are named. The process guide suggests decision rules (e.g., consensus, majority), group cultural norms, voting processes, and other important constructs for the upcoming dialogue.

The charter may define the timing, venue, and needed support for all meetings. Specific end products are referenced, as are performance metrics. A code of conduct or ground rules may be included as well. In totality, the process charter becomes the principal guidance tool for the collaboration. It serves as the law and the process, and empowers the process guide with well-understood parameters of responsibility. A draft of the process charter is presented to the dialogue participants at the process kickoff meeting. It is then modified as needed and ultimately accepted and endorsed by the participants as their own.

20.4.2 Stakeholder Group Composition

Perhaps the single most important step in a collaborative process is determining who will participate in the dialogue. Typically groups of more than about 28 become unwieldy. Constraining the size and shape of the proverbial table thus becomes a major process question. For a FacDCA it is critical to establish a DCA team that balances management and technical personnel across all stakeholders, with a focus on implementation beyond decision resolution. To support this, a few core DCA team members participate with the mission of understanding all aspects of decision resolution in order to carry the team strategy through DCA process implementation. (For a detailed discussion of DCA team formation during FacDCA, see Chapter 21.)

During the snowballing process of conflict assessment, interviewees are asked to name groups and individuals who have a legitimate stake in the collaboration. Through repetition, the process guide quickly learns to distinguish the real stakeholders from the pretenders. Further, she learns who is known and respected by the affected communities.

Generally speaking, process guides identify organizations and individuals that control funds, understand the technical liabilities, and are responsible for public health and welfare. A broad list of candidate participants is compiled and organized to achieve a balance in geography and perspective. The decision rules defined in the process charter aid the process guide in defining the critical mass required (e.g., specific communities should be able to express concerns as a voting block and thereby slow down, if not stop, the process).

Once the process guide has sculpted the numbers, the list of candidate participants must be arrayed according to the filters used for qualification. The most effective of these filters involves running candidate participants through the gauntlet described in the five criteria for participant selection:

Knowledgeable. Participants must come into a collaborative process with a certain level of base understanding of the technical, political, and/or socioeconomic underpinnings of the issues at hand. The process guide is a coach, not a teacher.

Rational. The legends of collaborative dialogue are littered with processes ruined because of the "just say no" types who say no at their own peril. Participants must be able to demonstrate the ability to listen, process information, and occasionally alter preexisting notions.

Representative. Participants must be representative of a larger constituent group. Because it is a rare dialogue that allows all persons from all affected communities to sit at the table, one individual often represents a broader cohort, so it is important to have someone who can effectively address all viewpoints.

Accountable. The representative should have processes in place that ensure constant communication with his or her cohort, and accountability to it, in decision making. In ideal situations, the individuals selected to participate in a collaborative dialogue will be empowered to speak on behalf of their cohort. In those instances, the cohort ensures that its representative is relaying its opinions and desires.

Committed. All too often, participants in collaborative dialogue are not committed to participate in the entire process. This can be a fatal flaw. Without commitment, the dialogue becomes a revolving door through which new and old participants are constantly shuffled. Institutional memory is challenged and the dialogue becomes a repetitive exercise of two steps forward and one step back. Before naming a participant, the process guide must review the conflict assessment as well as the charter and correctly gauge the commitment requirements and convey expectations to candidate participants.

20.4.3 The Road Map for Dialogue

This is where distinctions begin to appear among TFD, DBP, and FacDCA. In TFD, the process guide develops a sequence for decision making in which one decision builds on another. In DBP and FacDCA, decision making is often viewed as a systematic process with individual options scaled and weighted and interconnected via mathematical modeling. TFD tends to rely more on qualitative assessments and group dynamics. DBP and FacDCA tend to rely on mathematical assessments and probability theory and advanced program management experience. Whether the process guide opts for TFD, DBP, or FacDCA, he must explicitly structure the dialogue in a way that creates a logical progression of consensus building and agreement. The road map must be conveyed *a priori* to all participants so that they can prepare, confer, and formulate their interests in each issue.

Professional process guides tend to try bounding the scope and duration of collaborative dialogue as they follow the road map. Agendas are designed and managed according to the dialogue's ebb and flow. The best process guides do not manage dialogue with a stopwatch; instead, they guide it to the point of diminishing returns. Conversations are not stopped at a specific time; groups move on because there is little new content or creative thought on a specific item. Just as many embrace the ethos "think globally, act locally," process guides must think of the big picture and the tasks required for completing the entire dialogue, but they manage the dialogue in a way that creates a safe environment for participants to contribute at their own pace and not that of a timekeeper.

20.4.4 Metrics and Measures for Success

What is not measured is not managed. Or, as Yogi Berra said, "If you don't know where you are going, you might wind up someplace else." The conflict assessment should shed light on what end products are required. It may also address the intent of developing given products and the goals that are sought through implementation—in some sense previewing the intended results of implementing forged agreements. As the dialogue proceeds, all efforts should be directed toward the following:

- Agreement on some predetermined final product.
- Acceptance, enthusiasm, and buy-in not only for a final product but also for the implementation of programs, policies, and procedures that help to realize project goals.
- Developing constructive, solution-oriented relationships that transcend the boundaries of the current dialogue.

20.5 PROCESS GUIDANCE

Over the 20-year history of collaborative processes in the environmental policy arena, two main schools of thought have emerged. Some practitioners believe that there should be concrete standards for professional performance. They have occasionally attempted to regiment process design and guidance, establishing checklists, routines, processes, and benchmarks for success. Other practitioners believe that success in collaborative dialogue defies that type of approach. They believe that each and every dialogue is different because of data and information, technical issues, human dynamics, and politics. To these practitioners, every dialogue is unique—fraught with its own minefields and pitfalls.

We embrace the latter philosophy that no two collaborative dialogues are alike. This philosophy imposes much greater responsibility on the process guide than might normally be assumed. We believe that the burden is on the process guide to

- Create a safe environment.
- Establish common ground and trusting relations with each and every participant.
- Maintain complete mastery over the dialogue vocabulary as well as the technical, the political, and the socioeconomic dimensions of collaborative problem solving.
- Identify and reduce the impact of pseudo–decision makers (obstacles, inefficiencies, and nonbinding agreements).
- Encourage the development of long-lasting relationships through collaborative dialogue.
- Be vigilant and aware of peripheral interpersonal conflicts that impact the group process.

Regardless of the collaborative tool chosen, these six elements of process guidance are critical to a successful outcome and essential for establishing a safe environment for all participants.

20.5.1 Safe Environments

This is the highest priority for a process guide. People are wired differently; there are introverts and extroverts. We all process information in different ways, and no two people look or act the same. Our emotions on any given day are shaped by what we eat, whom we see, and the crises we face. Some people best process information visually, others aurally, and still others kinesthetically. Any and all of these factors shape what we say and how we participate in a group setting.

The process guide must create an environment in which participants can process information in the most constructive way. He or she must also reach for the most effective means to draw out some participants and push other more dominating characters back. The process guide must foster an air of creativity such that nothing that comes out in the group ideation process is viewed as over the top, outlandish, or just plain stupid. Mistakes are the seeds of brilliance. The process guide must ensure that all are free to contribute regardless of how far afield their ideas may be.

Further, and though there are differing perspectives on this, it is important for a process guide to bring the right tenor and cadence to a collaborative dialogue. Some dialogues require a degree of gravitas or formality; others can and should be lighter and more fun.

20.5.2 Trust

For the process guide, trust is power, but it is a two-way street. Transparency in the process and in decision making is crucial. In addition, with personal knowledge of what motivates each participant, the process guide can easily deflect or defer red herrings and other digressions. Trust is not earned overnight; it begins during the conflict-assessment process and continues through coaching and counseling in collaborative dialogue—and it must be nurtured constantly. As such, it is labor intensive. Many process guides give this element short shrift, and it hurts them later. Wizened process guides never underestimate the importance of establishing good and positive relations among all stakeholders. The time invested pays dividends.

20.5.3 Mastery

When all share a common body of knowledge, there is respect among participants and between the participants and the process guide. Each environmental issue has its own unique vocabulary and interactions. It is nearly impossible for a process guide to deliver good outcomes, recorded for institutional memory, without a full and complete understanding of the words, laws, acronyms, and even customs commonly used in discourse. This, too, is labor intensive, but the time committed to learning is not wasted. Use of technical facilitators during DBP and FacDCA ensures that the process guide not only is familiar with language and laws but also has the necessary experience with facilitation.

20.5.4 Decision Makers

In the most ideal situations, participants in collaborative dialogue are the ultimate decision makers. The gauntlet referred to earlier attempts to include only those participants that are representative and accountable to a larger group. Yet often it is important to realize that participants are empowered by those they work for to make decisions within the confines of the collaboration and ultimately to implement the will of the participant group—either nominally or in real terms.

Even before dialogue begins, the process guide must identify and reduce the impact of pseudo–decision makers—those who do not have true decision-making authority. She must overcome obstacles and inefficiencies and the temptation to allow the group to endorse nonbinding agreements. Sometimes these only become apparent during the dialogue. When that happens, it is imperative that the process guide work with the parties to ensure that decisions represent a broader and implementable will.

20.5.5 Relationships

Relationships are crucial to a group process from the initial kickoff to the commitments delivered at the very end. The process guide must create the platform and the means for people to bond—not through icebreakers (these are often perceived as silly one-time exercises that never really foster cohesion among a group or its subsets) but through a combination of teamwork, progress, and achievement. The stronger the relationships are, the greater the likelihood that the participants will embrace group commitments. The deeper the relationships are, the greater the likelihood that the participants can function long after the process guide's involvement ends. Many process guides work hard to make it so that they are not needed beyond a certain date. They attempt to work themselves out of a job by building participants' capacity to work as a team as opposed to a collection of individuals that need a referee.

20.5.6 Vigilance

Process guides must be extraordinarily vigilant about the tone and tenor among parties. It is important to remember that if all parties in a collaborative dialogue were in complete agreement and totally independent and reliable, neither collaborative dialogue nor the process guide would be needed. That is not the state of the world, however, and thus the need. Because the balance is ever-shifting, the process guide must always have a finger on the group's pulse, ready to intervene and redirect as necessary.

20.6 CONCLUSION

Multi-stakeholder dialogue is a powerful tool for advancing policy and leveraging action. When the right problem is addressed by the right participants in the right forum, with the right process design and guidance, people can move mountains.

CHAPTER

Facilitated Decision Consequence Analysis

21

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21.1 INTRODUCTION AND OVERVIEW

Facilitated decision consequence analysis (FacDCA®) utilizes the technical tools and DCA principles discussed in previous chapters while maintaining an increased focus on the psychological traps of decision making and stakeholder buy-in. Achieving long-term, binding agreement among stakeholders can be greatly affected by the psychology of decision making, which includes anchoring, sunk cost, status quo, confirming evidence, and risk aversion. These feed into the formation of each stakeholder's worldview and organizational agenda.

21.1.1 Competing Agendas

Competing agendas among decision makers are the primary drivers of inefficiency and communication gaps in development of a DCA or, for that matter, execution of any project. They are the elephants in the room. In environmental remediation, competing agendas can include the desire of the regulatory agent to demonstrate maximized, conservative protection of the population; the desire of the environmental contractor to generate work for his staff and defend his technical recommendations; and the desire of the client or property owner to reduce cost and accelerate the work schedule. These agendas appear to be contradictory on the surface. However, neutral technical facilitators trained to bring these agendas to light, quantify their impact, and provide cohesive balance to the DCA can overcome such obstacles.

Specifically, through facilitation and the modeling of the DCA process, one can bring all parties together by delving deeper into participants' "need behind the need." The regulatory agent's true desire is to demonstrate responsible, well-documented actions to the public that he or she serves. In the DCA this can become a means objective that drives the collection not necessarily of more data but of better data based on a well-documented decision logic that can be clearly communicated. The environmental contractor can then demonstrate his efficient contribution to the team through streamlining the scope of work for the current

DOI: 10.1016/B978-1-85617-797-9.00021-6

project while increasing the probability of winning additional, similar work in the future. The client is made aware that shortcuts and the lack of stakeholder buy-in early in the process will create greater cost and administrative burdens when viewed in terms of total project life cycle.

Unresolved conflicting agendas will derail a DCA, if not during the development stage, then during implementation. A DCA can be derailed before the process starts through one or more of the following pitfalls:

- Overrepresentation of one party versus another when selecting the team to complete the DCA.
- Demonstrated biases by the technical facilitator.
- Data hoarding by one group as a power play for control.
- Developing a flawed problem statement intended to match a preconceived, limited view of the issue at hand.
- Limited objectives (means and ends) that only address the needs of one organization or group participating in the DCA.
- Selecting alternatives to fit preconceived conceptual models before conducting a robust problem diagnostic and establishing objectives.
- Gaming performance metrics to mathematically stack the deck in favor of the alternative that satisfies a narrow constituency.

21.1.2 FacDCA Implementation

If the obstacles just listed are overcome during development and a solid DCA is produced, the next opportunity for conflict comes during the implementation stage. The DCA is not simply a plan that can be developed by one group of individuals, then thrown over the fence and executed by a separate group not involved in its development. Although its executors may have the best of intentions, and the DCA may be thoroughly documented, corporate knowledge of the vetting process and advances made in the interpersonal group dynamic during the FacDCA are lost if there is no continuity between development and execution. This loss is the most effective way to disconnect strategy from execution and degrade the momentum of the process.

Recognition of these challenges has led to the development of FacDCA, which takes a group of decision makers from the early stages of group formation through the long-term execution of the strategy and decision-based partnering (Chapter 22). Overall, FacDCA consists of three primary phases:

Phase 1: Structuring

- Define decision makers (DCA team).
- Develop shared understanding of the present state of nature.
- Determine decision triggers.
- Define problem/decision (problem diagnostics).

Phase 2: Evaluation

- Brainstorm objectives and performance metrics.
- Brainstorm alternatives.

- Calculate consequences and trade-offs.
- Develop decision trees.
- List uncertainties/address data gaps.
- Develop simulation models.

Phase 3: Agreement

- Implement.
- Partner.

During the structuring phase the team is defined, all data are assembled into a comprehensive GIS format and distributed, and the triggers driving the need for a decision as well as the problem statement are defined. Many of these elements are similar to those of a traditional DCA; however, the FacDCA facilitator focuses on laying the groundwork for improving the group dynamic from initiation through execution and often uses caucus as a means for hearing all stakeholder views. One-on-one, listening caucuses are instrumental in defining the technical and emotional issues at hand and in allowing each party to speak freely with the facilitator or mediator. More often than not, the listening sessions reveal that most parties feel they are not being heard by the others. Throughout the process, careful attention is given to the fact that decisions are made by people, not data, and that everyone participating has to feel that he or she has a valid, meaningful stake in the process.

However, not everyone can efficiently participate in the full process. Many times in environmental conflict resolution, the stakeholder groups, as well as the partnering teams, are large (more than 40 members). Completing a DCA with 40 people actively engaging can be an exercise in managing chaos. In addition, these groups are more often than not unbalanced in the participation level of varying organizations. For example, a government client may have 35 representatives in the room, including service agency officials, environmental contractors, installation personnel, and command, whereas the regulatory agency may have one to three. Such an unbalanced team, either consciously or not, generates defensiveness in the outnumbered party.

In FacDCA, therefore, unlike in traditional DCA, the facilitator will evaluate the direction of the process, define the optimal balance of technical and managerial team members, ensure that at least two team members are responsible for moving the DCA through execution, and balance the members across organizations. In this way, from a group of 40, 10 to 12 are thoughtfully assembled as the DCA team, to which the remaining participants assign decision authority and trust. This is no small task, but the benefits are expedited decision making, balance in the final decision, and continuity through execution.

Once set, the DCA team moves into the evaluation phase, which mimics the basic DCA process defined in previous chapters. However, given the balanced thoseonstruction of the team, the objectives are more reflective of all organizations participating. Likewise, the alternatives are expanded to include those that some participating parties felt were not being given significant attention or were not being addressed. The consequences and trade-offs of alternatives are then calculated in real time and thoroughly vetted with the team. Everyone is heard; no objective or alternative is granted more weight or importance than another. At the end of the day there is a game plan developed from a common understanding of the data and a balanced, technical approach to gaining group consensus.

The DCA game plan is then taken back to the original 40-member group, not for approval—that authority has been assigned to the DCA team going in—but for communication. Communicating the technical depth of the analysis, active participation and buy-in from technical and upper management personnel, and commitment of the DCA team members responsible for execution solidifies the overall comfort level of the team with the DCA conclusions and action plan. The team thus becomes viewed as responsible guardians of the strategy who will work integrally with the larger group through implementation. Once the evaluation phase is successfully completed, group members are dismissed and, for the most part, they consider the DCA complete.

However, agreement on the DCA is not the end of the process. Continued active engagement during the agreement phase is instrumental in avoiding the second most common reason that conflicting agendas derail or adulterate the DCA. During implementation, it is easy to myopically focus on data collection and operations while forgetting about the greater strategy into which these activities feed. The old habits of emotional or advocacy-based decision making filter into the team dynamics, and conflicting agendas once again take hold and sway the process.

For best results, the FacDCA technical facilitator remains involved and establishes decision-based partnering (DBP) among the 40-member group, continuing to monitor the agreement phase for successful execution of the DCA and providing support for "tune-ups" as data is gathered and time elapses. Learning becomes the team's objective, whether it is labeled adaptive management or systematic planning. The DCA is allowed to function as a living strategic document and consensus-building tool, which must be constantly molded to address a changing state of nature.

The following sections discuss a FacDCA project completed at Shaw Air Force Base (AFB). Although the project demonstrates exceptional teamwork during the structuring and evaluation phases, it stands as a lesson that the agreement phase is critical to successful DCA implementation.

21.2 CASE STUDY: SHAW AIR FORCE BASE

Shaw Air Force Base is an Air Combat Command (ACC) facility located in Sumter, South Carolina, 37 miles east of Columbia. It has approximately 3570 acres, with several operable units (OUs) governed under the Resource Conservation and Recovery Act (RCRA) by the South Carolina Department of Health and Environmental Control (SCDHEC). Base activities are primarily industrial; however, the

Base is surrounded by both private residences and agricultural land. The groundwater has been impacted by volatile organic compounds (VOCs) associated with two operable units, OU2B and OU2D. Contamination has migrated west off Base and impacted private drinking water wells.

Corrective measures studies (CMSs) recommended continued operation and optimization of a hydraulic containment system that has been extracting and treating groundwater from the western Base boundary since 1997. The system was originally installed as an interim measure to protect the surrounding population. (See Chapter 4 for a discussion of the impact of sunk cost on moving from an interim measure to a final remedy.)

The Shaw AFB partnering team agreed to participate in a facilitated third-party technical review, and FacDCA focused on final remedy selection for two operable units (OU2B and OU2D). During the structuring phase, two decisions/problem statements were identified and addressed:

Decision 1. What is the appropriate point of compliance at which to measure attainment of cleanup?

Decision 2. What is the most appropriate final remedy for OU2B/OU2D given the selected criteria for protection of human health and the environment?

21.2.1 Groundwater Characteristics

Shaw AFB (the Base) rests atop three geologic formations, two of which contain the hydrogeologic units that are specific to OU2B and OU2D:

- OU2D: Duplin Formation—top of unit 214.9 feet mean sea level (msl).
- OU2B: Black Creek Formation—Upper Black Creek (top of unit 171.1 feet msl); Lower Black Creek (top of unit 160.3 feet msl).

The shallow aquifer (Duplin) demonstrates a southeastern groundwater flow direction. The Duplin was derived from eroded geologic formations and appears to communicate with the Upper Black Creek east of the flightline, where the sands of the two formations are no longer separated by clay. The Black Creek is a major drinking water aquifer in the Sumter area and underlies the entire Base. The upper and lower portions of the Black Creek are separated by a substantial clay unit. Groundwater flow direction in this aquifer is to the west (Figure 21.1).

Sources are present in both OU2B and OU2D. Forty years after source release, the VOC-impacted groundwater plume had migrated and the boundaries had stabilized at its maximum extent (MW-29B), as noted in the 1996 trichloroethylene (TCE) plume contour (Figure 21.2). Assessment of the plume characteristics from 1996 and 2002, however, indicated areas of increasing groundwater concentrations or source locations (Figure 21.3). All sources noted in OU2B and OU2D were being hydraulically contained by the OU2B groundwater hydraulic contaminant system at the time of the project.

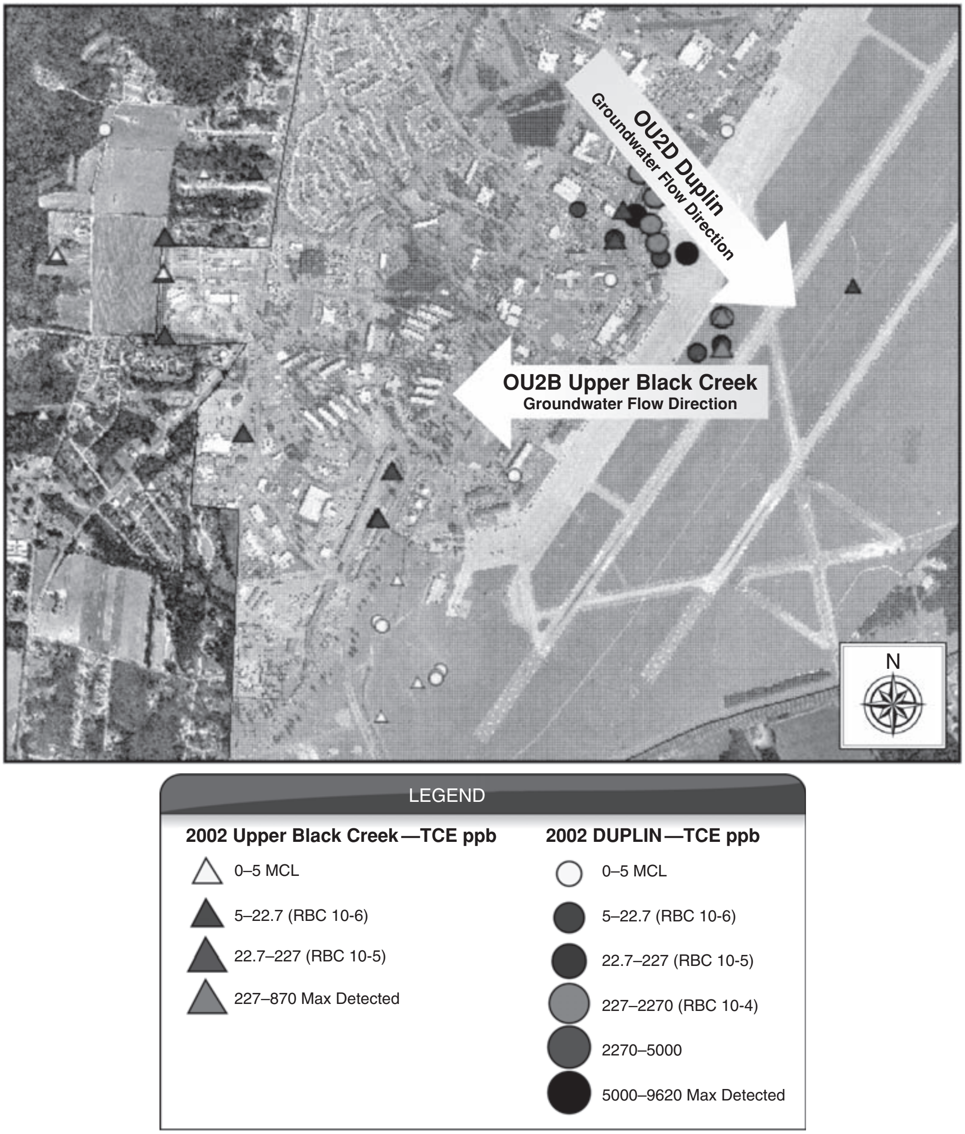

FIGURE 21.1

Groundwater migration within operable unit.

Aggressive groundwater recovery off Base had apparently facilitated an increase in contaminant mass movement toward the western Base boundary (Figure 21.4). This effect was obvious from examination of the average TCE concentrations in three domains of the site from 1996 to 2002. The three domains represented the source area, an area between the source and the Base boundary

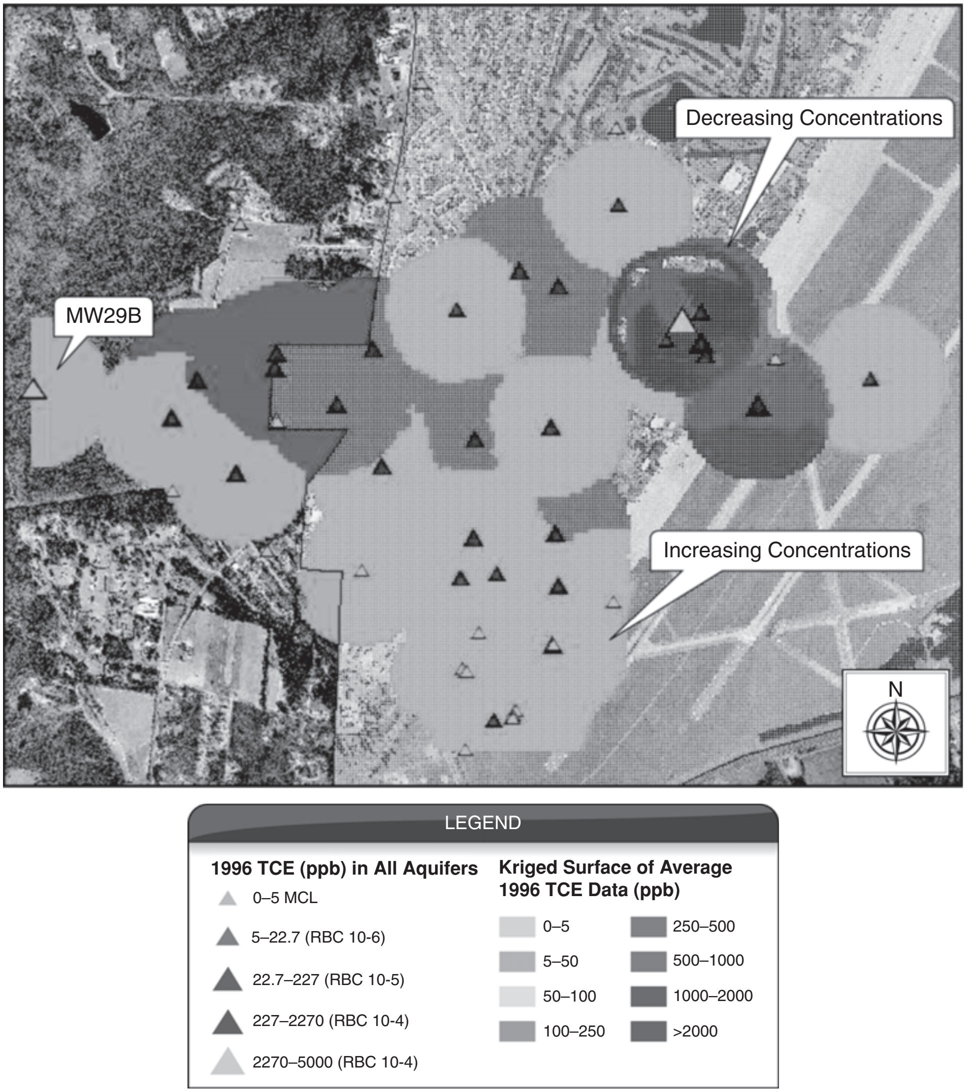

FIGURE 21.2

Maximum extent of 1996 TCE plume.

(referred to as Mid Plume), and an area beyond the Base boundary (referred to as off Base).

From 1996 to 2002 there was an 18-parts-per-billion (ppb) increase in Mid Plume domain concentrations at a 95 percent confidence level. Furthermore, the summation of the Mid Plume and off-Base domains demonstrated the overall change in the plume outside the OU2D source area pre- and post-treatment.

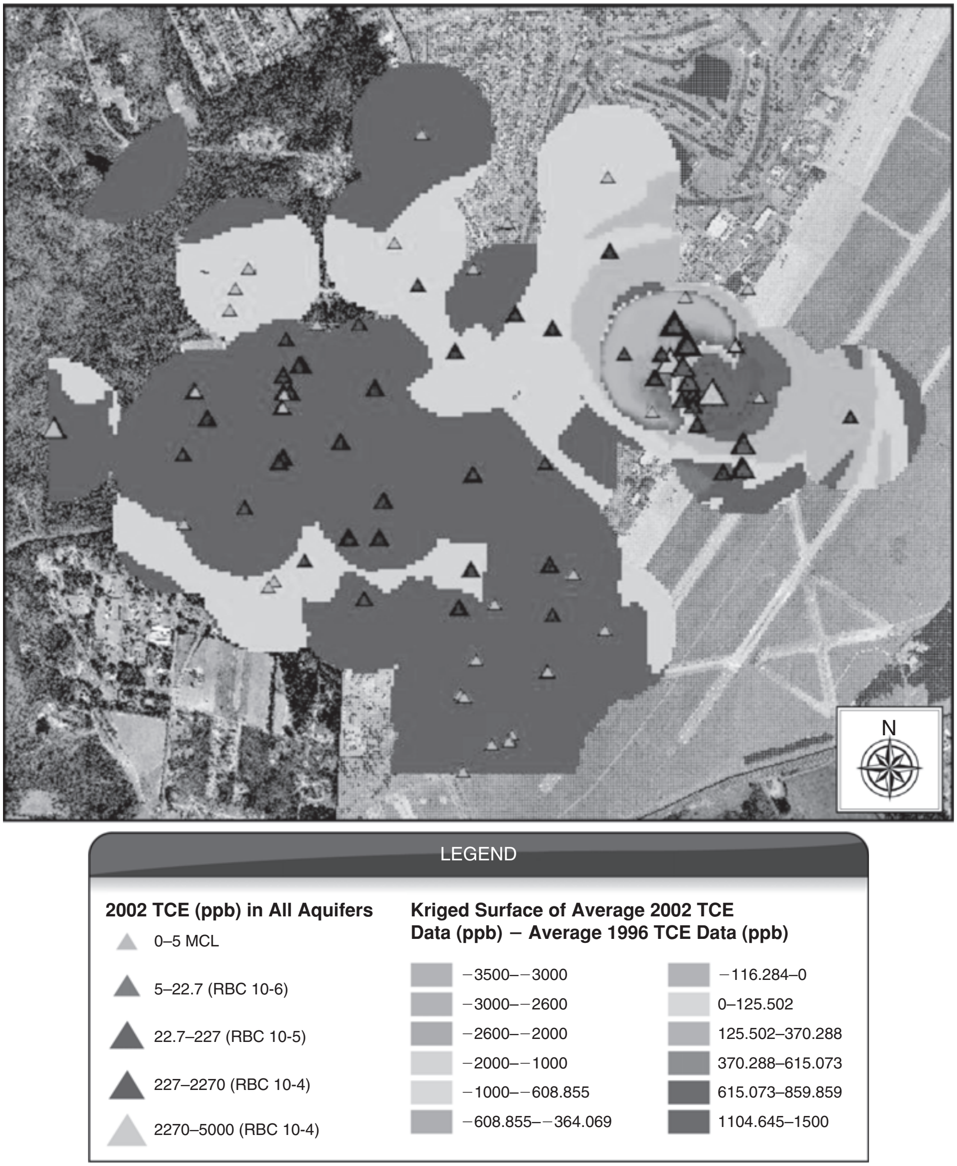

FIGURE 21.3

Subtraction on TCE surface maps developed from kriged groundwater data (2002 – 1996).

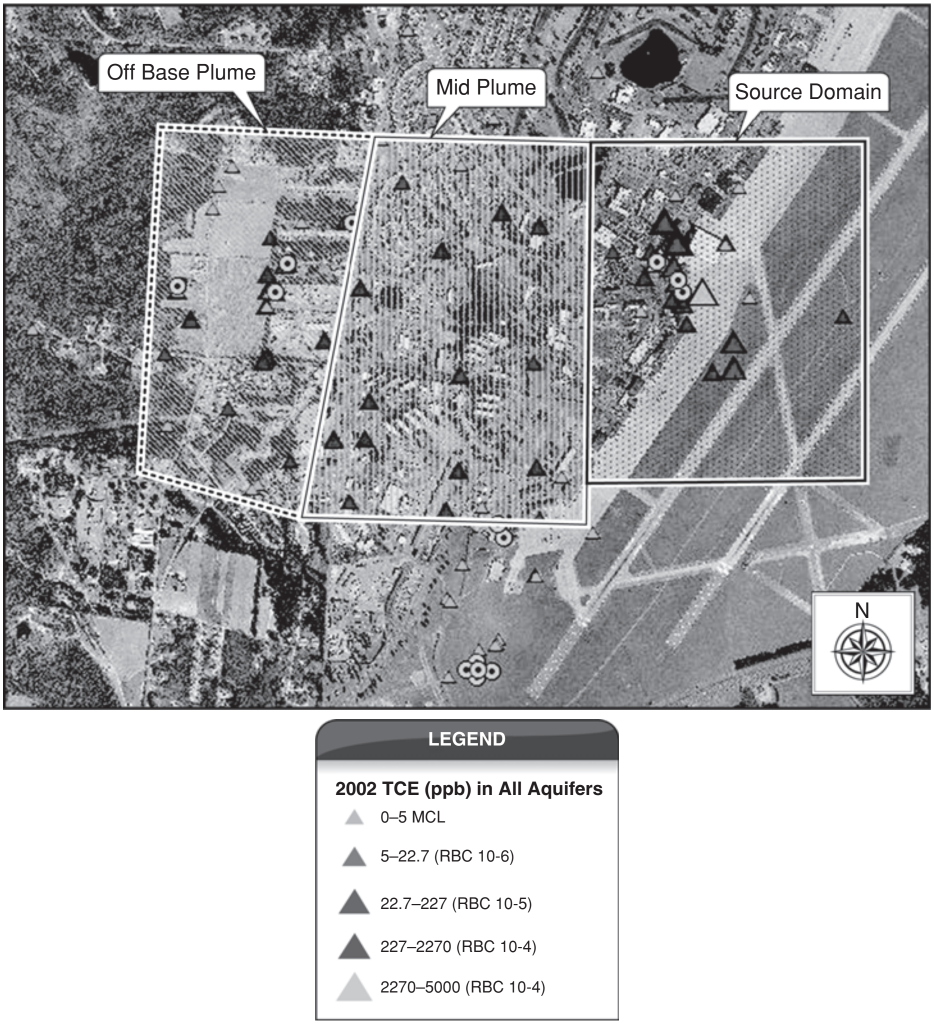

FIGURE 21.4

Evaluation of plume domains.

In 1996, the combined Mid Plume and off-Base 95 percent upper confidence level (UCL) estimate of groundwater TCE concentrations was 115.58 ppb. This concentration increased to 146 ppb in 1998 following initiation of groundwater extraction, but decreased to 112.92 ppb by 2002.

The domain average concentrations also provided an approximation of the half-life of the total mass of TCE contamination within the area. Based on the plume-wide concentration mass reduction from 1996 to 2002, the half-life for TCE was estimated to be approximately 6 years. This 6-year half-life provided an estimated attenuation time of 60 years for the average plume concentrations to reach the maximum contaminant level (MCL) of 5 ppb.

Figure 21.5 demonstrates the presence of daughter products associated with the biodegradation of TCE and tetrachloroethylene (PCE). Mann-Kendall analysis indicated that select wells throughout both aquifers had a decreasing concentration trend. The distribution of the suite of PCE breakdown products and the statistical trends indicated the presence of a dynamic soil ecosystem capable of metabolizing the chlorinated solvents.

The measured time series for chlorinated solvent concentrations indicated that TCE and PCE would likely persist off Base at levels above their respective MCLs for

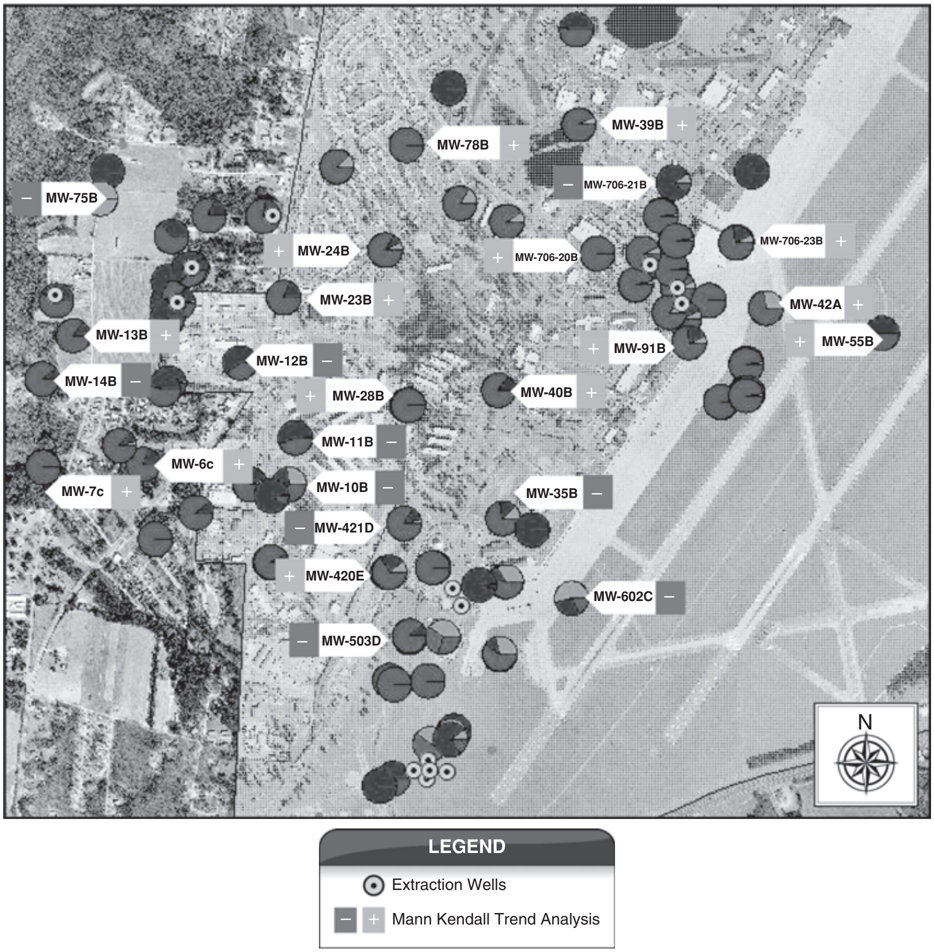

FIGURE 21.5

Biological activity and trend analysis.

years, with or without active intervention. However, the chlorinated solvents would eventually attenuate to the MCL throughout the plume domain regardless of the level of active intervention. This conclusion was based on the following conditions: (1) the mass of TCE was finite, (2) biological and/or chemical conversion was occurring, and (3) dilution and attenuation were active phenomena.

Whatever measure was utilized for managing the contaminated groundwater, some type of control mechanism would be necessary for a minimum of 24 to 30 years to manage human contact with the water. The control mechanism effective in stopping contact with the groundwater under an aggressive treatment approach would likely be equally effective under less aggressive approaches.

21.2.2 Common Objectives

Common objectives were established for decisions 1 and 2 as a result of a facilitated session with the core partnering team. The eleven objectives agreed on by SCDHEC and USAF complied with the National Contingency Plan (NCP) and were measured in terms of relative benefit. These objectives were expanded to include USAF mission preservation, making clear the values of the Shaw AFB team as a whole. It was important to this team that human health and the environment be protected while preserving the Base's mission and the economic viability of Sumter County. The common objectives were

- Preventing exposure to groundwater above acceptable risk levels.
- Preventing or minimizing further migration of the contaminant plume outside of the OUs.
- Preventing or minimizing migration of contaminants from the source area.
- Returning groundwater to beneficial uses whenever practicable.
- Reasonable cost.
- Public acceptance.
- Mission preservation.
- Implementability.
- Short-term effectiveness.
- Robustness (i.e., the ability of a system to maintain its functionality under the full range of likely stresses. In environmental remediation, robustness includes the ability of a restoration to be self-sustaining and insensitive to future human actions).
- Minimize time until closure.

Once these objectives were established by the core partnering team, a 12-member DCA team was assigned to work through the remaining DCA process.

21.2.3 Decision 1

What is the appropriate point of compliance at which to measure attainment of cleanup? Shaw AFB's use of MCLs as the OU2D and OU2B cleanup standards had been formalized in primary decision documents associated with the OUs. However, the point of compliance (POC) at which the attainment of the standard was to be measured had not been established. The goal of decision 1 was to clarify the consequences associated with POC selection. The problem statement had to be developed to accurately show the connection between the decision triggers (the conditions driving the decision) and the decision itself. Additionally, given interconnected decisions, the order in which decisions were addressed was critical. In this project, the success of remedial options could not be accurately reviewed without establishing the most appropriate point at which to measure success. Point of compliance was the focus of decision 1.

Consequence analysis for decision 1 evaluated the following POC alternatives:

- MCL throughout the plume
- MCL interior to the Base boundary
- MCL at the Base boundary
- MCL off Base

Such an analysis is the calculation of performance metrics and review of what these calculations reveal about the appropriateness of each alternative in meeting the listed objectives. Figure 21.6 summarizes the consequence analysis for decision 1 in this project. The Base boundary was determined to be the most appropriate point of compliance.

21.2.4 Decision 2

What is the most appropriate final remedy for OU2B and OU2D given the selected criteria for protection of human health and the environment? Since the 1988 detection of TCE in drinking water wells, the USAF aggressively pursued risk management options at the Base. Short-term goals for protection of human health were met through interim remedial actions. Decision 2 laid the groundwork for strategic planning not only for risk management but for long-term, effective liability reduction. All remedial options reviewed in decision 2 were evaluated assuming cleanup to MCLs at the Base boundary.

Consequence analysis for decision 2 evaluated these remedial alternatives:

- Passive options:
  Monitored natural attenuation (MNA)
  Land purchase with MNA
  Land use controls with MNA

- Containment options:
  Existing hydraulic containment system for OU2B
  Optimized hydraulic containment system for OU2B
  Land purchase with optimized OU2B hydraulic containment system
  Land use controls with optimized OU2B hydraulic containment system

Decision 1 — OBJECTIVES	ALTERNATIVES: 1 MCL Throughout Plume	2 MCL Interior to Base Boundary	3 MCL at Base Boundary	4 MCL Off Base	INTERPRETATION
1 Prevent Exposure to Groundwater above Acceptable Risk Levels	0.41	0.75	1.00	0.50	High desired; Low least desired
2 Prevent or Minimize Further Migration of Contaminant Plume outside of SWMU	1.00	1.00	1.00	1.00	1 Acceptable; 0 Unacceptable
3 Prevent or Minimize Migration of Contaminants from Source Area	0.00	0.48	0.62	1.00	High desired; Low least desired
4 Return Groundwater to Beneficial Uses Wherever Practicable	1.00	0.45	0.27	0.13	High desired; Low least desired
5 Cost	$19,691,796	$14,588,744	$11,269,569	$10,501,791	Low desired
6 Public Acceptance	0.12	0.14	0.08	1.00	High desired; Low least desired
7 Implementability	1.00	1.00	1.00	1.00	1 Acceptable; 0 Unacceptable
8 Short-Term Effectiveness	0.03	0.67	1.00	0.25	High desired; Low least desired
9 Mission Preservation	0.00	1.00	1.00	1.00	High desired; Low least desired
10 Robustness	−1.67	1.00	1.00	1.00	High desired; Low least desired
11 Schedule	0.02	0.04	0.04	1.00	High desired; Low least desired
Cumulative Utility	1.92	6.53	7.01	7.88	High desired; Low least desired

FIGURE 21.6

Consequence analysis for decision 1.

- Engineered treatment/containment options:
  Land purchase with OU2D hydraulic containment system
  Land use controls with OU2D hydraulic containment system
  Optimization of OU2B hydraulic containment system with OU2D hydraulic containment system
  In situ OU2B and OU2D source area treatment with optimized hydraulic containment system for OU2B

Performance metrics were established for each objective, and the value of each alternative in meeting the objectives was quantified through consequence analysis (Figure 21.7). The decision 2 analysis illustrated that the containment and treatment alternatives provided limited additional utility when compared with passive alternatives. This outcome was a result of the fundamental characteristics of the utility concept as it related to this plume.

Utility is primarily associated with the relationship between resource and resource need. As the need for the resource increases, its utility increases. In this instance, the groundwater was needed only as a drinking water supply in the portion of the plume beyond the Base boundary. However, the need was not overwhelming; an alternative water supply was available and had to be provided for an extended period of time under any scenario. As a result,

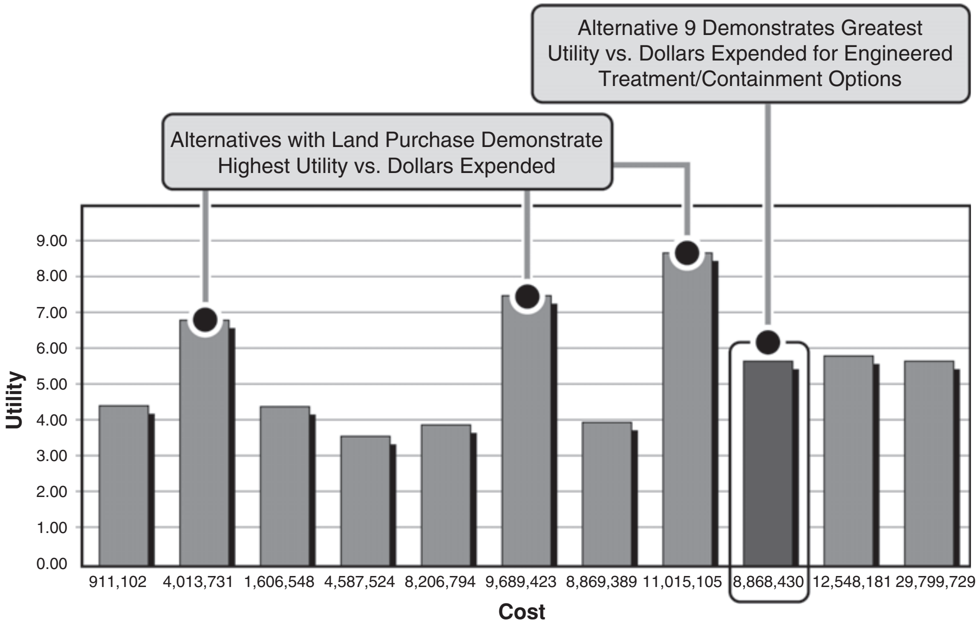

FIGURE 21.7

Decision 2 cumulative cost versus cumulative utility.

the utility of onsite containment or treatment relative to passive alternatives was reduced.

Utility is also derived from the reduction of uncertainty. There is both intrinsic and extrinsic value in the certainty of outcomes, as it reduces constraints on future actions. However, in this case it was not clear whether containment or treatment reduced or increased uncertainty relative to passive alternatives.

Containment presented a conundrum. A hydraulic barrier required establishment of a reverse gradient at the property boundary. Unfortunately, this could not be achieved without a cone of depression that would accelerate the movement of contaminants toward the Base boundary. As the reversal of off-Base flow increased, the plume on property could experience increased lateral smearing. Treatment presented different concerns. It was unlikely to create or exacerbate plume smearing, but its efficacy was highly uncertain.

The greatest utility was associated with timely and permanent restoration/control of groundwater off Base. Therefore, it was determined that concurrent operation of the OU2B and OU2D systems should be a transient activity. Combined operation of both systems would ensure minimal dissolved plume migration during the time the plume was stabilizing; however, long-term effectiveness of the system was minimal. Moreover, given the mass shift effect of the system, long-term operation of OU2B (with or without optimization) would provide little utility and might prolong the overall amount of time that concentrations exceeding MCL would remain off Base.

It was recommended that once OU2D operation was established, empirical evidence of plume dynamics and restoration rates should be generated with an *a priori* agreement on the performance metric to be utilized in data analysis. OU2B would be shut down and monitoring increased. It was also recommended that the OU2B system and extraction wells remain operable in the event that adverse plume movements were recognized. Additionally, a plan providing performance metrics to measure the effectiveness of the OU2D system would be established prior to initiating system operation. Agreement on the measures of low-value added operation was to be reached before the system was turned on, with a clear path to OU2B and OU2D site closure developed.

21.2.5 Data Gaps and Informational Objectives

During completion of the FacDCA, data gaps were identified and follow-up forensic and statistical analysis carried out to provide additional detail on the true source of the off-Base TCE plume. Example applications of these tools are provided in Chapters 15 and 16.

The Environmental Isotope Laboratory of the University of Waterloo in Ontario carried out a limited environmental investigation of the isotopic features of PCE, TCE, and dichloroethylene (DCE) in groundwater samples from the two principal plumes in the study area. The samples were collected from monitoring wells screened in the Duplin and Upper Black Creek aquifers and tested using mass spectrometry. The primary objective was to determine whether differences in manufacturers could be detected between source material in OU2B, OU2D, and off Base.

The specific objectives of the investigation were as follows:

- To measure the carbon ($^{13}C/^{12}C$: $\delta^{13}C$) and chlorine ($^{37}Cl/^{35}C$: $\delta^{37}Cl$) isotopic ratios for PCE, TCE, and DCE in groundwater samples from the two principal groundwater plumes.
- To evaluate the uniformity (or lack thereof) of the isotopic features for each chemical across and between each groundwater plume.
- To examine the changes in isotopic composition of the PCE and TCE in each suspected plume as a function of concentration gradient to uncover evidence for substantial biodegradation of the compounds in the groundwater system.
- Using isotope fingerprinting, to determine the possible source relationships for each chemical within and between the two plumes.

The observations were as follows:

- Based on changes in isotope patterns between parent and degradation compounds, there was limited biodegradation of the compounds within the boundaries of the groundwater plumes.
- The TCE found in OU2D had significantly different isotopic features from those of the TCE found in OU2B, meaning that the TCE in these two plumes likely arose from different sources.
- The TCE found in the OU2D nearest the area of highest concentration was reasonably similar in isotopic composition to that found in lower-concentration wells within the same plume. This suggested a similar source for the TCE within the plume.
- In OU2B, the PCE found near the area of highest concentration was somewhat different in isotopic composition than that found in presumed down-gradient wells in the plume. These isotopic differences could have resulted from the fractionation of PCE during limited down-gradient biodegradation or from chronic low-level inputs of PCE to the plume down-gradient from the presumed source area.

Concurrent with the forensics analysis, a statistical analysis of all OU2B and OU2D chemical-of-concern data was conducted. The available groundwater data represented a multivariate data set, with each sample consisting of measurements of multiple analytes, including chlorinated solvents and various VOCs. Chlorinated solvents from different sources are known to have different chemical signatures; these differences can be exploited to distinguish between multiple sources of groundwater contamination.

In this analysis three separate statistical tests were performed to assess the multiple sources of contamination and to investigate the possible migration of groundwater contaminants from the Base to off-Base wells. The three tests performed included

- Principal component analysis
- Student's *t*-test
- Mann-Whitney test

The objectives of the statistical analysis were

- To determine whether there was statistical correlation between the OU2D and OU2B plumes.
- To determine whether spatial patterns of contamination were indicative of off-Base sources of contamination.
- To determine the range of correlation to assess the extent, if any, of off-Base migration of contamination from the OU2D or OU2B plume.

Overall, the forensics study, statistical analysis, and empirical data reviewed indicated the following:

- No evidence of an off-Base source of PCE or TCE contamination existed in 2003.
- Off-Base contamination was likely a result of migration of contaminants from the OU2B source material.
- The OU2B area had little to no contamination originating from the OU2D sources.
- There was no conclusive evidence of off-Base migration from the OU2D plume.

These results added context to the FacDCA and supported the selection of engineered treatment and containment options targeting both the OU2B and the OU2D. However, lingering concerns over the source of off-Base contamination remain unresolved within the partnering team.

21.3 CONCLUSION

The FacDCA process is designed to address long-term commitment to decisions, not just short-term decision evaluation. All phases of FacDCA—structuring, evaluation, and agreement—are equally important in achieving that goal. As the team works through the initial DCA, questions arise, informational objectives need to be met, and new information must be evaluated as the course to achieving success is consistently tended. If the old habits of decibel- or agenda-driven decision making are allowed to creep back into the process, the value of the original FacDCA is undermined and progress to site closure is stalled.

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CHAPTER

Decision-Based Partnering

22

Megan Duley, Daphne Williams, Kandi Brown, Frank Werner, Robert Barrett

22.1 INTRODUCTION

The Department of Defense (DoD) established partnering to reduce the administrative cost of extended conflict during environmental restoration. Partnering is an effort among numerous organizations to operate as a team to meet common objectives. The traditional DoD partnering approach is tiered and hierarchical. The structure consists of tiers made up of individuals with increasing levels of authority. Tier-I has core technical competency, tier-II has cleanup authority on a state level, and tier-III has regional policy authority. These tiers work together to address issues that periodically require elevation to a higher level for resolution. This process can be time consuming and does not facilitate rapid decision making.

The objectives of the partnering approach are to make communication more interactive; to reduce disputes by working together to plan site activities; and to develop ground rules for interaction among clients, regulatory agencies, and contractors. The partnering objectives represent a highly productive behavioral/procedural change that fosters teamwork and cooperation so that all parties are working toward the common goal of protecting human health and the environment.

Having all parties meet face to face promoted interaction and allowed trusting relationships to develop. However, the downside of non-value-added communication and numerous, lengthy meetings became readily apparent: positional bargaining, advocacy divorced from data, compromises of technical quality for appeasement's sake, and a lack of value-focused thinking.

Decision-based partnering (DBP) is a departure from the tiered, time-consuming, traditional approach. It is a new way of doing business in response to the rapid decision making required to succeed with performance-based restoration (PBR) and performance-based contracts (PBC), such as those initiated for the United States Air Force (AF) at Seymour Johnson Air Force Base (SJAFB) in 2005. DBP provides a feedback mechanism to identify problems early and avoid risk deference late in

DOI: 10.1016/B978-1-85617-797-9.00022-8

the contractual period, allowing for course adjustments to improve the likelihood of success.

The primary objective of DBP is rapid progress toward site closure through meetings with stakeholders who can make critical decisions regardless of the traditional hierarchy. The tier-I team identifies and prioritizes key issues, which are then scheduled for resolution depending on their impact on site closure and risk management. Communication is more focused and effective and results in issue resolution in a shorter time frame. The benefits of this structure include

- Improved communication and awareness of state/regional policy issues
- Faster resolution of issues
- Reduced administrative costs
- More consistent decision making
- Greater success in closing sites.

22.2 APPLICATION OF DBP TO SUPPORT AF OBJECTIVES

In executing PBR using PBC, the AF identified a need for a partnering structure that would enhance communication, encourage stakeholder agreement on objectives, and allow rapid decision making. DBP encompasses several facilitation techniques while using the building blocks of Decision Consequence Analysis (DCA™). This provides a structured approach to achieve contracting, scheduling, and performance objectives as illustrated by the following steps:

Step 1: Evaluation/assessment. Observe group dynamics and decision making styles; review specific statutes; assess the regulatory environment; and conduct an independent, third-party evaluation of site exit strategies and schedules.

Step 2: Prioritization. Develop the schedule of resolution (SOR) identifying key decision points along the paths to site closure, while incorporating all AF Defense Planning Guidance goals issued by the secretary of defense. The secretary of defense provides goals, priorities, and objectives, including fiscal constraints, for defense agencies developing program objectives.

Step 3: Benchmarking/metrics. Develop situational criteria and performance metrics to address decision points and track progress.

Step 4: Monitoring/adjustments. Monitor performance metrics and make adjustments to ensure progress.

By following the DBP steps, meetings can be scheduled to focus on specific decision points and milestones that require group consensus, thereby becoming more productive. Team members gain a better understanding of roles and expectations, which leads to agreement on risk assessment and progress toward site closure.

22.3 PILOT STUDY: APPLICATION OF DBP AT SEYMOUR JOHNSON AIR FORCE BASE

Implementation of DBP at SJAFB has accelerated progress toward site closure for environmental restoration program (ERP) sites by providing improved communication, effective exit strategies, and decision-making transparency among tier-I team members. The tier-I partnering team includes representatives from the Air Force Center for Engineering and the Environment (AFCEE), the base (SJAFB), the United States Army Corps of Engineers (USACE), the North Carolina Department of Environment and Natural Resources (NCDENR), and contractors responsible for achieving the performance objectives and milestones in their remediation contracts.

The DBP concept was introduced to the SJAFB tier-I team at a meeting in 2005, after a technical facilitator observed and assessed (DBP steps 1 and 2) the team dynamics, communication styles, decision-making preferences, and each member's interests and motivations. (Technical facilitators are skilled in facilitation and mediation techniques and have years of technical program management experience in environmental restoration.)

A pilot study of the effectiveness of DBP was used to initiate the process at SJAFB. At the time of the study, two legacy ERP contractors were responsible for up to five sites and a new contractor, under a Fixed Price Remediation with Insurance PBC, was responsible for sixteen sites. The sites were in various phases of restoration, such as investigation, remediation alternative evaluation, remedial action (RA) implementation, and RA operation and maintenance.

Review of remediation strategies, contractor's technical approaches, and anticipated progress revealed key areas hindering progress and resulted in the following recommendations:

Avoid using legacy contractors with more flexible contract mechanisms to conduct investigative activities at PBC sites. This violates the PBC risk-bounding objectives and could result in unconstrained costs. Considering the value/use of the data versus the time and cost of obtaining it focused data collection and use to support specific goals.

Ensure the base team (AFCEE, SJAFB, USACE, and contractors) agrees on goals and presents them as a team. All team members must be aware of site closure strategies, applicable regulations, and schedule implications, and they must agree on achievable objectives.

Establish decision criteria prior to taking action. It was assumed that all parties were aware of cleanup goals and paths to site closure; however, comments clearly indicated a disconnect in that area. The team needed agreement on goals and site closure strategies. Using decision trees to guide activities and define endpoints was very effective in reaching team consensus.

Standardize the decision process. When team members become familiar with a consistent decision/conflict resolution process, they can work more effectively toward site closure.

Resolve discrepancies between DoD and state (NC) requirements early. A conflict between DoD risk-based cleanup criteria based on land use (industrial, residential, etc.) and the more stringent North Carolina statutory cleanup criteria that protect groundwater has delayed progress at some sites. Elevation of this issue to tier-II resulted in a policy statement from NCDENR that verified their position. DBP supported addressing the conflict head on, so the team was able to develop alternatives to achieve the desired goals.

Because the AF team has representatives from four agencies, phone calls prior to partnering meetings are sometimes required to reach a consensus, which is necessary before discussion with NCDENR. This process was developed to avoid the stalemates inherent in the "them versus us" days of regulatory negotiations and to

- Ensure agreement among AF representatives.
- Improve preparedness to address key decisions.
- Identify relevant decision makers.
- Ensure that options presented are consistent with AF policy, technically valid, and achievable under contract and funding constraints.

Meetings became more effective, and the frequency was reduced from six per year initially to two or three per year currently. The importance of decision-focused discussion with the regulator cannot be overemphasized. Tier-I meetings became more effective by focusing on specific decision criteria for site closure and developing decision trees to ensure progress. A decision tree is a tool that provides a logical sequence through specific activities and possible outcomes/consequences to expedite progress toward a specific goal.

During the pilot study, DBP step 1 revealed problems that were hindering decision making and delaying progress. The SJAFB team followed the recommendations from the DBP assessment and conducted site closure workshops, discussed regulations and policies, and reviewed the DCA™ process to improve performance.

DBP step 2, prioritization, focused on the SOR for tracking decision points, decision resolution, steps toward site closure, contract schedule requirements, goals, and overall program progress at SJAFB. An illustration of the SOR is presented in Figure 22.1. Decision points are questions that need to be answered or disagreements that need to be resolved prior to moving forward. Team members need to be thoroughly familiar with the SOR because it is the primary tracking tool that indicates the health of the program. It is updated regularly and is used to identify schedule priorities, pending deadlines, and potential bottlenecks. SJAFB had most site decisions and closures near the end of the contract period, shifting most of the risk and liability to the performance deadlines. Step 2 of the pilot study allowed the team to reprioritize sites and add resources to eliminate bottlenecks.

The SOR supports the third DBP step, benchmarking/metrics, by documenting actual versus planned activity and provides a mechanism to identify site- or

Seymour Johnson Schedule of Resolution
All Open Sites to Closure

Task Name	Duration	Start	Finish
Decision-Based Partnering Benchmark Tracking	1Day	Tue 11/8/05	Tue 11/8/05
PBC POP	1698 Days	Wed 5/25/05	Fri 11/25/11
RRS High RIP DPG Goal	1Day	Fri 9/28/07	Fri 9/28/07
RRS Medium RIP DPG Goal	1Day	Fri 9/30/11	Fri 9/30/11
RRS Low RIP DPG Goal	1Day	Fri 9/28/12	Sun 9/30/12
Program Duration	2127 Days?	Fri 10/1/04	Mon 11/26/12
BFSA Path to Closure (ST-01, SD-02, SD-03 and ST-05)	1338 Days	Wed 11/9/05	Fri 12/24/10
Funded Through Closure	1Day	Thu 12/29/05	Thu 12/29/05
Remedial Action Plan	83 Days	Mon 7/24/06	Wed 11/15/06
St-01/ST-05 (H)	1316 Days	Fri 12/9/05	Fri 12/24/10
DPG Goal (Attained)	1Day	Fri 9/28/07	Fri 9/28/07
Pre-Design Investigation Workplan ST-01 and ST-05	26 Days	Wed 5/17/06	Wed 6/21/06
Remedial Action Plan	68 Days	Thu 7/6/06	Mon 10/9/06
ST-01/ST-05 RD	257 Days	Fri 12/9/05	Mon 12/4/06
RAC	268 Days	Tue 1/2/07	Thu 1/10/08
RAO (LTM)	523 Days	Mon 10/1/07	Wed 9/30/09
Site Closure Report	81 Days	Mon 4/12/10	Mon 8/2/10
Site Closed	1Day	Fri 12/24/10	Fri 12/24/10
SD-02 (H)	129 Days	Wed 11/9/05	Mon 5/8/06
SD-03 (H)	129 Days	Wed 11/9/05	Mon 5/8/06
SS004 Path to Closure (H)	934 Days	Wed 5/25/05	Mon 12/22/08
Funded Through Closure	1Day	Wed 5/25/05	Wed 5/25/05
DPG Goal (Attained)	1Day	Fri 9/28/07	Fri 9/28/07
Decision Point	69 Days	Tue 2/7/06	Fri 5/12/06
Leak Test Data	69 Days	Tue 2/7/06	Fri 5/12/06
RAO (Surfactant Injection, MPE)	756 Days	Tue 11/8/05	Tue 9/30/08
Achieve GCLs Standards	88 Days	Tue 4/1/08	Thu 7/31/08
Site Closure Report	1Day	Tue 9/30/08	Tue 9/30/08
Site Closed	1Day	Mon 12/22/08	Mon 12/22/08
LF006/LF008 Path to Closure (NR)	1839 Days	Wed 11/9/05	Mon 11/26/12
Funded Through Regulatory Site Closeout	1Day	Thu 12/29/05	Thu 12/29/05
RA (LTM Only Currently)	1019 Days	Wed 11/9/05	Mon 10/5/09

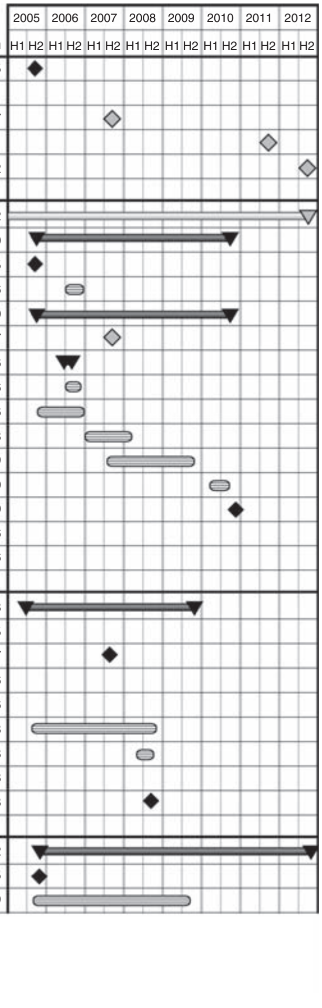

FIGURE 22.1

Excerpt from the SJAFB Schedule of Resolution.

media-specific decision points requiring the team's attention to expedite resolution. SJAFB used site-specific decision trees, developed with facilitation guidance during tier-I meetings, to reach agreement on a sequence of activities that would lead to site closures. By achieving a team consensus on the activities that follow specific outcomes, decisions were made early and progress toward site closure was ensured. Figure 22.2 illustrates a site-specific decision tree that was utilized at SJAFB.

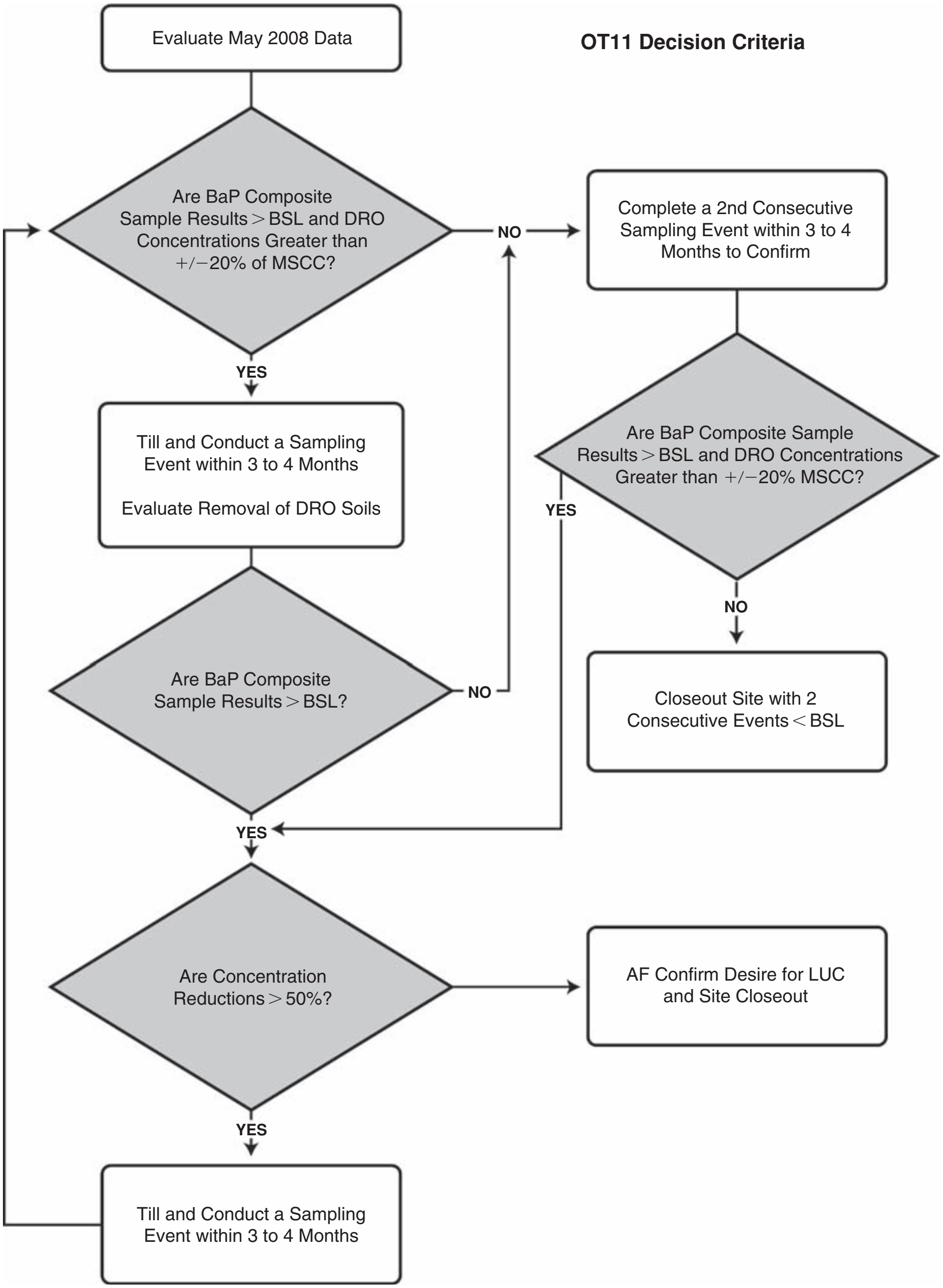

FIGURE 22.2

Seymour Johnson Air Force Base decision tree.

The fourth step in the DBP process, monitoring/adjustments, tracks performance metrics against benchmarks and makes adjustments to keep as close to the planned schedule as possible. It also indicates when performance exceeds expectations—that is, when goals are achieved ahead of schedule. When the SJAFB team's performance metrics were compared to the AF Program's goals' benchmark, several areas had markedly improved. When DBP was initiated in 2005, decision-point resolution time was 456 working days due mainly to lack of decision criteria, lack of agreement between the AF and NCDENR, and a 240-working-day review period for a site closure document. After just one year using DBP, decision-point resolution had decreased to 30 to 90 working days.

Close scrutiny of performance metrics revealed inefficiencies in the partnering process and led to improvements in team productivity. Implementing a shorter decision-point resolution time and using DBP techniques helped the team reach agreement on closure strategies much faster than before DBP. This led to remediation activities being started sooner and resulted in rapid progress toward site closure. Figure 22.3 illustrates the increase in site closures realized by SJAFB. The progress correlates well with the shift to PBR efforts and the inception of DBP in 2005.

The SJAFB is on or ahead of schedule, and all sites are expected to achieve closure by 2012. Implementation of the DBP process has enhanced team effectiveness, improved tracking capabilities, and resulted in significant progress toward closure for all ERP sites.

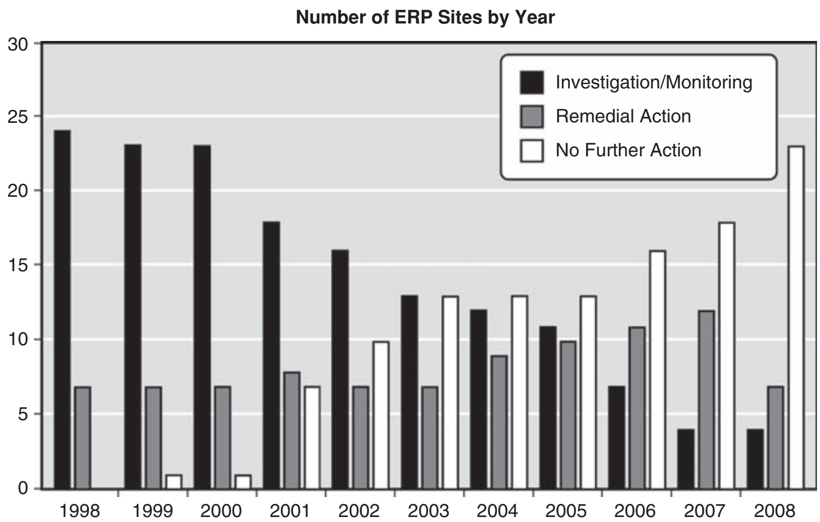

FIGURE 22.3

SJAFB Environmental Restoration program progress, 1998–2008.

22.4 CONCLUSION

Implementation of DBP at SJAFB promoted fast-tracked decisions, accelerated remediation activities, reduced risk, and led to more rapid site closures. The SJAFB team was selected above all other AF installation teams to receive the 2007 General Thomas D. White Environmental Award for innovative contracting, technical expertise, comprehensive partnering, and community outreach. It was further recognized by winning the 2008 Secretary of Defense Environmental Restoration Award, Installation category, in competition with all DoD installations worldwide.

CHAPTER

Performance-Based Contract Crafting

23

Daphne Williams, Kandi Brown,
James Henderson, Robert Barrett

23.1 INTRODUCTION

In the President's Management Agenda for Fiscal Year 2002, President George W. Bush states that the government likes to begin things, to declare grand new programs and causes, but that good beginnings are not the measure of success. What matters is completion: performance and results. It is not just making promises but making good on those promises. The Management Agenda went on to discuss long-term expected results, stating that better performance is based on an assessment of the expected outcomes that are relative to what is actually being achieved. This is the essence of performance-based contracting (PBC): focusing on performance and results rather than solely on process. Because of this focus, PBC can result in higher-quality work and increased accountability, which both advance sustainability objectives.

PBC is a contracting approach in which outsourced work is performed with minimal focus on process. Maximum emphasis is placed on end results with measurable performance criteria and contractor incentives. PBC transfers financial risk to potential bidders and seeks improved certainty on budgets and schedules in exchange for reduced transaction interference and a risk premium. In an ideal situation, the transfer may actually be more cost effective than conventional approaches if reduced transaction costs offset the risk premium.

By definition, risk involves an "exposure to a *chance* of injury or loss" (Random House, 1966). Risk can be based on injury or loss as it relates to human health, ecological health, political and financial welfare, and so forth. If chance is low and/or definable, risk can be bound. If chance is uncertain, indefinable, and highly probable, risk cannot be bound. All uncertainty carries risk; all risk, however, does not necessarily contain uncertainty to the degree that it becomes unboundable. It is the quantification of uncertainty that allows risk to be effectively defined and contractually managed.

DOI: 10.1016/B978-1-85617-797-9.00023-X

The key to successful PBC is a common understanding of the structural uncertainty that cannot be overcome by the experience or skill of the bidder. This structural uncertainty has two components:

- Regulatory criteria for final measurement of success (closure)
- Physical constraints of the remedial action

For example, with regard to regulatory criteria, the measure of success for a groundwater restoration system may range from reaching the maximum contaminant level (MCL) throughout the plume to attaining a risk-based standard that protects a previously agreed on point of compliance (POC). Both may be equally protective of realistic receptors, but the cost differential may be in the tens if not hundreds of millions of dollars.

For another example, with regard to physical constraints, a performance standard of MCLs may be mandated (and the basis of bidding) and later discovered to be unachievable, perhaps after years of futile effort. The contract may require an endpoint, but a legal mandate to achieve something that is physically impossible is risk delay rather than risk transfer.

Organizations using PBC need to know and understand the uncertainty constraints and limits to risk transfer in PBC. Uncertainties can be driven by lack of data, regulatory demands, site location, and the like. As uncertainty translates directly to price, decision makers need to know about and make informed decisions on how much financial risk transfer can be afforded or is even reasonable. Performance-based contracting can be enhanced by using it selectively for sites at which uncertainty can be defined sufficiently to accurately quantify the benefits of the financial risk transfer. By performing this analysis up front, the organization can then move to mitigate the uncertainty and improve the quality of the PBC bidding by filling data gaps, developing regulatory agreements, or bounding the risk that is expected to be transferred to the contractor in the scoping process.

What is a performance-based contract? As stated earlier, a PBC focuses on performance and results rather than process. For the private sector, it provides an opportunity to transfer cost savings to a customer through creative thinking and technical initiatives. For the government, it means providing an opportunity to place contractual obligations on the true goals in liability reduction. According to the Department of Energy, PBC structures all aspects of an acquisition around the *purpose* of the work as opposed to either the manner in which the work is to be performed or broad and imprecise statements of work (DOE, 2000).

The benefits of a PBC are numerous and include the following:

- It maintains focus on the results rather than the process.
- It provides an opportunity for increased quality by tying the results to compensation.
- It increases accountability of both the contractor and the contractee.

Additional benefits include increased user satisfaction, expenditure efficiency, an opportunity to manage risk, and reduced scope creep.

The challenges can be just as numerous and may include the following:

- Lack of understanding regarding contractual obligations
- Poorly defined and poorly written statements of work (SOWs)
- Unobtainable and unrealistic performance standards
- Limited or nonexistent technical objectives
- Lack of surveillance to ensure progress toward the end goal

How does the PBC idea become reality? How do we direct contractual obligation to the true goals in liability reduction and at the same time ensure that all parties have opportunities for success? PBC reality can be achieved through a better understanding of the end goal and by structuring that goal into a contracting mechanism that realizes the potential for rewarding the fulfillment of promises. To craft such a contract, the following must take place:

- Clear definition of contract objectives:
  - Strong technical evaluation and facilitation services
  - Cost estimating and probabilistic forecasting
  - Selection of contract type (to match the risk being faced)
  - Contract development
- Bid evaluation and contract award
- Development of a surveillance plan

Defining the objectives associated with a PBC can be an arduous task. It requires an understanding of what is desired, what is reasonable, and what is legally defensible or necessary. Initially the perception of PBC was that an unrealistic goal was somehow contractually achievable or that all risk could be transferred to the contractor. For example, initial objectives might be to eliminate all risk associated with an environmental hazard; to remove all contaminated soil; to clean up groundwater to pristine conditions; or to restore the site to its natural state—and accomplish all of this within a 5- to 7-year period of performance (POP). However, what might be more reasonable, considering the site's defined land use type, would be to eliminate any type of potential exposure pathway so that the site can continue to function productively, and to ensure that human health and the environment are properly protected, all legal mandates have been met, and the client is able to logically and most efficiently manage its liabilities in the most cost-effective way.

To properly develop an executable SOW, several tasks must be completed:

1. Gather and evaluate all available and relevant data.
2. Understand the needs and wants of the property owner.
3. Understand current and future land use.
4. Become fluent in the legal obligations associated with the object of the procurement.

5. Develop technical performance objectives (TPOs) that are appropriate for the land use, the risk being faced, and the client's requirements.
6. Complete realistic cost estimating and probabilistic forecasting to support contract type selection.
7. Develop a SOW that allows the bidder the flexibility to develop an innovative and unique strategy to meet the TPOs.
8. Provide access to all data utilized during the development stage.

Gathering and evaluating environmental data are the backbone of successful procurement. As with all technical evaluations, the process is only as good as the data available. Junk in equals junk out—securing all relevant and defensible data and developing a tool that allows the transfer of that data are very important.

Of equal importance is consensus regarding the most achievable and favorable outcomes. Stakeholders come from varying positions and hold different worldviews; regulators, service centers, base personnel, and contracting agents have their own perspective on the most important aspect of a solicitation. PBCs can raise concerns for many stakeholders. For example, regulators may fear that the client will no longer be involved in the communication stream and that an aggressive contractor will be solely responsible for all future negotiations. The client may be concerned that its role in protection of its program will be diminished and that it will no longer participate in contract implementation. The service centers may be concerned with the successful implementation of the contract, while contracting agents grow weary over the requirements of assessing performance and obtaining payment.

Refocusing stakeholders on technical facts as opposed to emotions and fears requires skillful technical facilitation and a collaborative process that concentrates on the outcome of the contract rather than its management.

A deep understanding of regulatory requirements enables a focused technical evaluation of the possibilities from an informed platform. If the TPO is not technically sound and reasonable within the regulatory framework, the solicitation cannot be reasonably executed.

Once the legal and regulatory guidelines are known, the needs of the client understood, and all relevant and legally defensible data compiled and evaluated, appropriate and obtainable TPOs can be developed. To do this, however, a technical evaluation is paramount. A technical evaluation looks at the available environmental data, the contaminated media, the current and future land use, and the regulatory requirements and opportunities. The technical evaluator then compiles the information into a database and a geographic information system (GIS) to rapidly develop achievable scenarios for cleanup. These scenarios become the basis for cost estimating and probabilistic forecasting.

Technical evaluations help to create TPOs that allow for creativity and confident execution by the bidder. Without the technical evaluation, cost estimating is based on a static approach toward remediation. It considers only one scenario rather than building in the flexibility needed for innovation. Moreover, it limits the ability to accurately forecast the costs of reaching the project objectives or

TPOs. TPOs should be timely and challenging while focusing on the end goal of reducing the client's overall liability.

The evaluation and development of TPOs should be clearly defined within an executable SOW. Depending on the type of procurement, SOWs can be *functional specifications*, in which the language only requires the contractor to achieve an end result or TPO; *performance specifications*, which specify the means by which the TPOs are to be achieved; or *detail or design specifications*, the most restrictive, which define the process and procedures that must be utilized to meet the TPOs.

Although all types of SOWs can be effective, the functional specifications approach enables the most flexibility and ultimately the greatest opportunity for innovation and developing cost-saving strategies. It is critical, though, that the client understand the physical and legal constraints and associated performance uncertainties and not rely solely on a contractor's set of assumptions.

Once all elements of the procurement are in place and the solicitation is on the street, providing appropriate access to all available data ensures that the contractor can focus on developing a strategy that best addresses the liabilities. For every data gap or uncertainty identified, the risk versus the reward increases. To improve bid development, communication tools such as a GIS can enable the contractor to holistically visualize and analyze site conditions and critical uncertainties. The benefits of GIS in both the short and the long term are clearly recognized, as discussed earlier, and are shown with specifics in the project example to follow.

Gathering and communicating data in a relevant and productive manner, so that PBC solicitations are successfully awarded and implemented, goes beyond the development stage. Ensuring that an awarded contract is accurately and effectively managed requires clear communication and well-defined expectations. While developing TPOs to focus the contractor on what is most important, understanding that interim TPOs will be used as part of tracking progress toward the end goal is equally powerful. Ensuring that the contractor understands that a surveillance program will be implemented to manage overall progress facilitates the development of a performance standard verification plan (PSVP).

Many contracts are executed over broad time frames, and TPOs are achieved not within the first year but typically over several years of investigation and negotiation. Monitoring performance over time requires up-front negotiation and facilitation, including development of the PSVP. During PSVP development, strategies for monitoring progress are developed using statistical methods agreeable to all parties involved.

Geostatistical assessments are used to interpret and analyze environmental data and include determining spatial correlations, calculating accurate predictions, quantifying the accuracy of the predictions, and supporting the development of optimal sampling plans. Outputs from statistical assessments can be used to evaluate progress toward TPOs, or they can be used as representative technical metrics. The PSVP allows a third-party neutral observer to evaluate performance based on data rather than on activity.

23.2 CASE STUDY: MOODY AIR FORCE BASE

Moody Air Force Base (MAFB), located in southern Georgia, has a successful environmental restoration program. Its environmental remediation efforts date back to the early 1980s. Years of investigation, reporting, remediation, and negotiation have ensured that the base is moving toward a reasonable horizon for site closure, but there are still opportunities to optimize performance. For that reason, it was determined that MAFB would benefit from the development of a basewide PBC focused on reducing the overall liability of the United States Air Force (USAF) through site closure, long-term monitoring and remediation optimization, and long-term reduction in life cycle costs. Historic use of cost-plus contracts would be replaced with a competitive PBC solicitation to accelerate program progress.

As part of the initial process, technical facilitators were brought in to help develop a PBC solicitation. The goal was to look at all technical means of reducing MAFB's environmental liabilities while ensuring that the overall AF mission was protected and all uncertainties in the process captured and quantified.

Understanding environmental data is critical to developing the best strategy for effective management and decision making. Key to the successful development of a PBC in this project was assessing the environmental data associated with the base. MAFB was fortunate to have a robust database, extensive in both quantity and quality. Data processing and formatting the various layers allowed technical facilitators to develop a comprehensive basewide GIS. Multiple attributes were included in the GIS to permit all pertinent media (i.e., groundwater, surface water, soils, and sediments) to be considered. The final product included groundwater flow directions, buildings, roadways, taxi ways, and other impermeable surfaces, as well as wetlands and other surface water bodies. The result was a fully functioning tool that was able to support the technical and the geostatistical calculations.

The MAFB GIS was used for the third-party technical evaluation prior to the development of TPOs and in support of cost estimating and scenario development. The technical evaluation included detailed data analysis, such as a basewide well network optimization strategy, or variogram reduction analysis (VRA). Statistical optimization provides a legally defensible means to reduce the number of wells in a monitoring network without compromising the ability to accurately estimate trends, spatial extent, and directional patterns of a groundwater plume.

MAFB has an extensive well network. As with most groundwater investigation processes, groundwater monitoring-well locations were chosen based on proximity to the presumed source of contamination. The result was clusters of wells. Data from clustered wells tend to be highly correlated, providing redundant information regarding the spatial distribution of contaminants.

To assess the redundancy, statistical optimization was conducted using the MAFB GIS. First, a variogram was developed to assess the contaminant spatial correlation for trichloroethylene (TCE), the main chemical of concern (COC) (see

Chapter 15 for more details on this type of analysis). Using the output of the variogram, contaminant concentration maps were developed using kriging analysis to estimate the COC concentrations between data points or, in this case, groundwater wells. This process included calculating the standard deviation between the kriged surface of the original well network and the kriged surface of the optimized well network (Figure 23.1).

Once the standard deviations of the two data sets were viewed within a GIS, it was possible to identify the potentially redundant wells based on site knowledge, professional judgment, and the significance of the standard deviations. Regulatory guidance stated that any percent difference lower than the relative percent difference (RPD) for a given analyte was insignificant and thus that data point could be considered redundant. If the percent difference was significant, the wells were not considered redundant and thus not proposed for removal from the existing well network. If the difference was insignificant, the wells were determined redundant and removed.

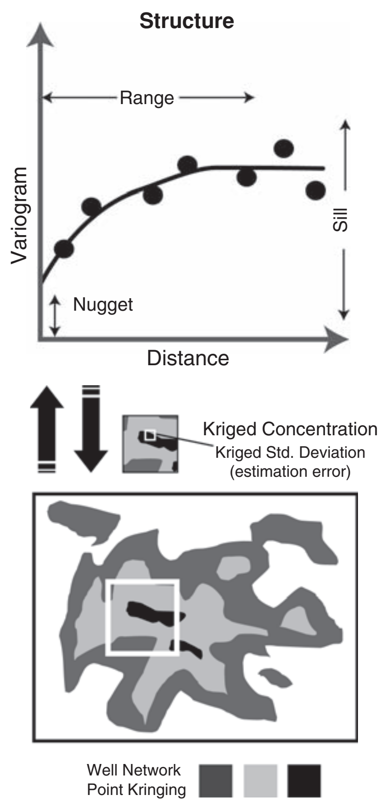

FIGURE 23.1

Geostatistical analysis.

After this analysis, it was possible to propose an optimized well network that was equally representative of the existing network in measuring the contaminant plume. In the case of MAFB, the resulting evaluation showed a significant potential reduction from the currently sampled 178 wells to an optimized network of 115. Figures 23.2, 23.3, and 23.4 provide a summary of this process.

The preceding well optimization evaluation was only one form of technical review conducted in support of MAFB SOW development. A comprehensive technical assessment was also completed for each of the 12 sites to be included in the solicitation. The most recent documents were obtained; they included corrective action plans and addendums, long-term monitoring reports, any correspondence between the base and the regulatory body, the Georgia Environmental Protection Division (GAEPD), and the Base Master Plan. In addition, a regulatory review of standard permitting guidelines was conducted, including a search for new programs that would provide opportunities for developing alternate concentration limits (ACLs).

Supported with the most recent analytical data, a fully functioning GIS, and a network of documentation, the evaluation phase began with developing technical scenarios for each of the 12 sites, including best-case, most likely, and worst-case scenarios. Best-case scenarios were typically assumed to have “no further action” (NFA) status, if reasonable; if NFA status was not reasonable, the action was assumed to consist of the removal of an engineered system followed by limited long-term monitoring. Most likely scenarios represented a slightly more conservative approach toward closure and reduction of LLCs. Worst-case scenarios were evaluated using the most conservative approach, assuming the maximum monitoring requirements and system operation.

The scenarios were developed by a technical professional based on knowledge of the sites, regulatory climate, and professional judgment. A second level of evaluation was completed by a neutral professional to “gut-check” the appropriateness of the technical assessment and the likelihood of scenario execution. On the basis of professional judgment, knowledge, and data, probabilities in the form of percents were assigned to each scenario representing likelihood of execution.

From the finalized scenario evaluation, Remedial Action Cost Engineering and Requirements (RACER®) cost estimates were developed for each scenario for each site, totaling 36 cost estimates. Using Oracle’s Crystal Ball software, probability distribution functions were applied to key cost drivers associated with each cost scenario to quantify the uncertainty associated with each RACER estimate. (See Chapter 10 for a discussion of model simulation tools.)

Some costs varied during the uncertainty analysis, including time to reach standard, volume of excavation, affected areas of soil vapor extraction (SVE) and bioventing systems, quantities of materials required for in situ bioremediation and chemical oxidation, and so forth. Probabilistic cost forecasts and 50 percent cost estimates for each site-specific scenario were then developed. Note that a 50 percent cost estimate is defined as the midpoint cost where there is a 50/50

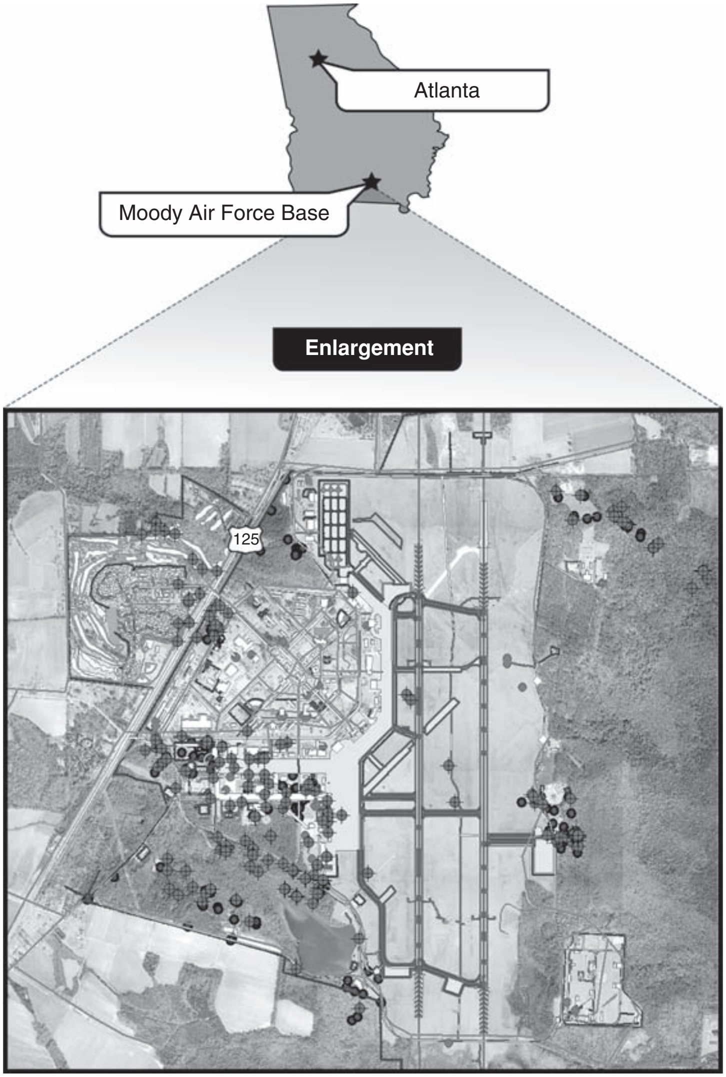

FIGURE 23.2

Moody Air Force Base TCE groundwater plume.

probability that the actual cost will be either higher or lower than the projected cost (Figure 23.5; see page 454).

Decision trees were developed with Palisades Corporation's PrecisionTree software (see Chapter 10) and used to create a combined probability for site-specific best-case, most likely, and worst-case cost scenarios. The combination of these scenarios under different probabilities of occurrence for each captured the reality that

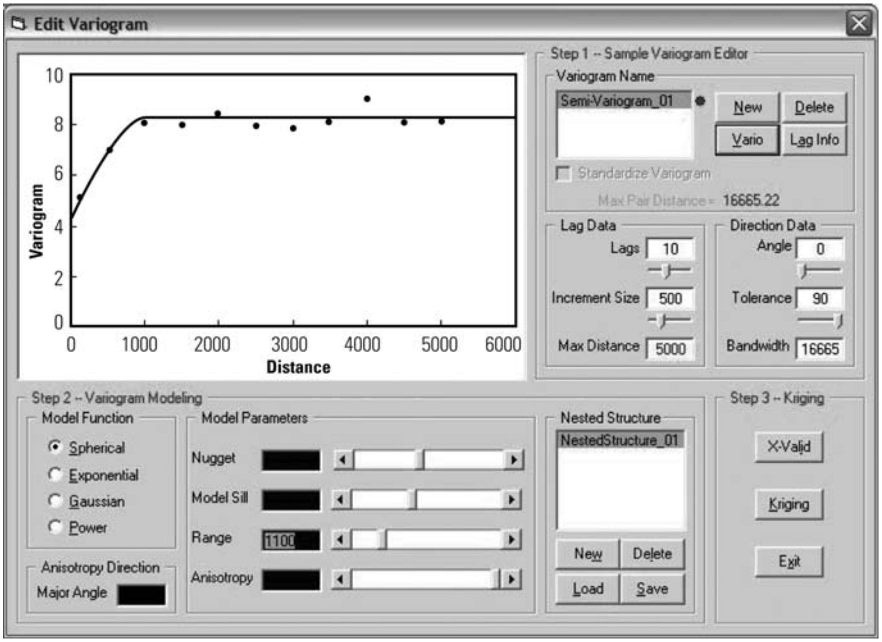

FIGURE 23.3

TCE variogram.

remediation decisions made in the present may change in the future. Actual implementation evolves over time, especially for projects that have a life span in excess of 30 years. For example, it is likely that, even if MAFB did not attempt to obtain favorable remedial action objectives, these objectives may be changed to much more conservatives ones in the future as the impracticability of permanent pump-and-treat systems with little chance of success becomes increasingly obvious.

Blended forecasts were developed based on these estimates, resulting in a total program probabilistic cost estimate, or rough order of magnitude. The probabilistic cost estimates were developed for the period of performance of the contract, which was 5 years, and the life-cycle cost effort. Both of these costs were used to develop cost curves that provided the ability to visually assess the consequences of each contract type.

Three contract types were evaluated in developing the MAFB PBC: cost plus incentive fee (CPIF), firm fixed price (FFP), and fixed price with incentive fee (FPIF). The type of contract chosen depends on the risk associated with it. Higher risk translates into higher costs, as shown on Figure 23.6. Contract types versus cost probabilities also show that the greater the standard deviation, the higher the risk potential for successful execution.

The MAFB cost and technical evaluation led to the determination that a CPIF was the most appropriate option. A CPIF is typically called for when the levels

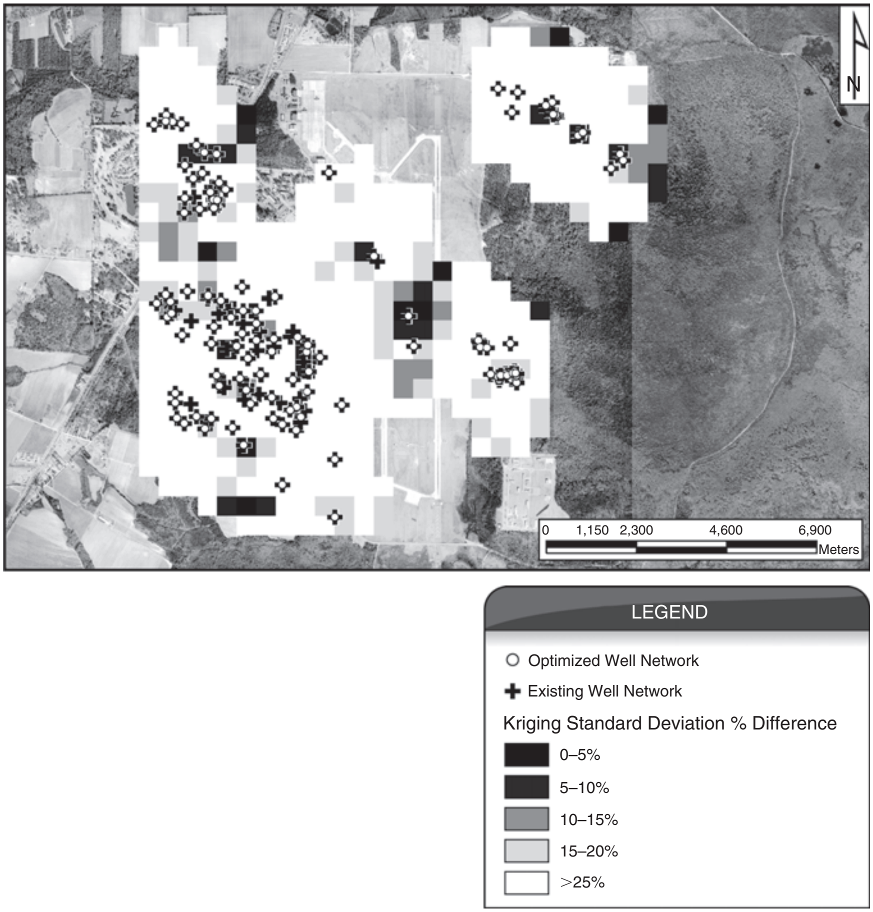

FIGURE 23.4

TCE kriged standard deviation difference map.

of technical and cost uncertainty are high, yet the probability of successful performance is also reasonably high. The cost-sharing arrangement between the contractor and the government was expressed as a percent ratio of the agreed-on target costs. For example, a 75/25 incentive share line means that the government pays 75 cents and the contractor pays 25 cents for every dollar spent above the target cost of the contract (DoD, 1969). However, in a cost savings example where the actual costs are lower than the target costs, a 75/25 incentive share line means that the government saves 75 cents and the contract earns 25 cents over and above the target profit or fee. All share line estimates are in accordance with the requirements of the Federal Acquisition Regulation.

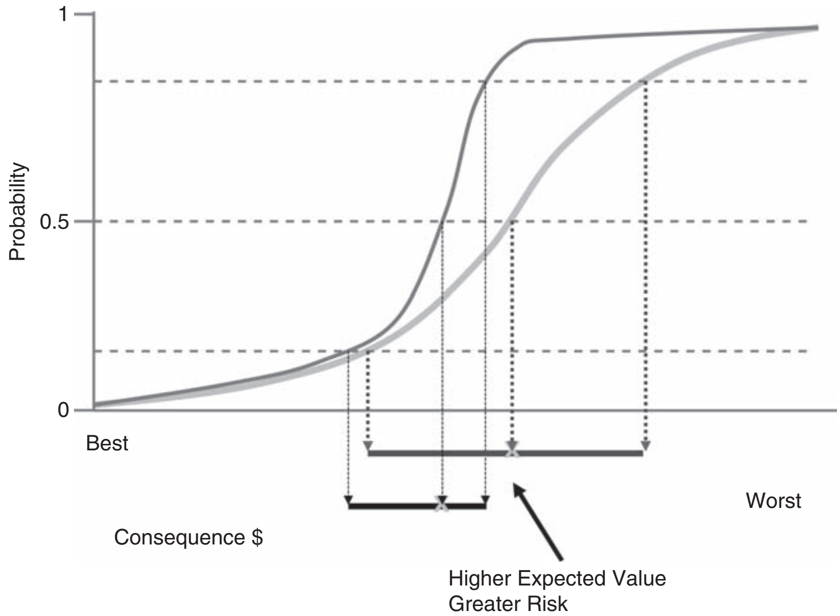

FIGURE 23.5

Consequence analyses, interpreting the cost curve.

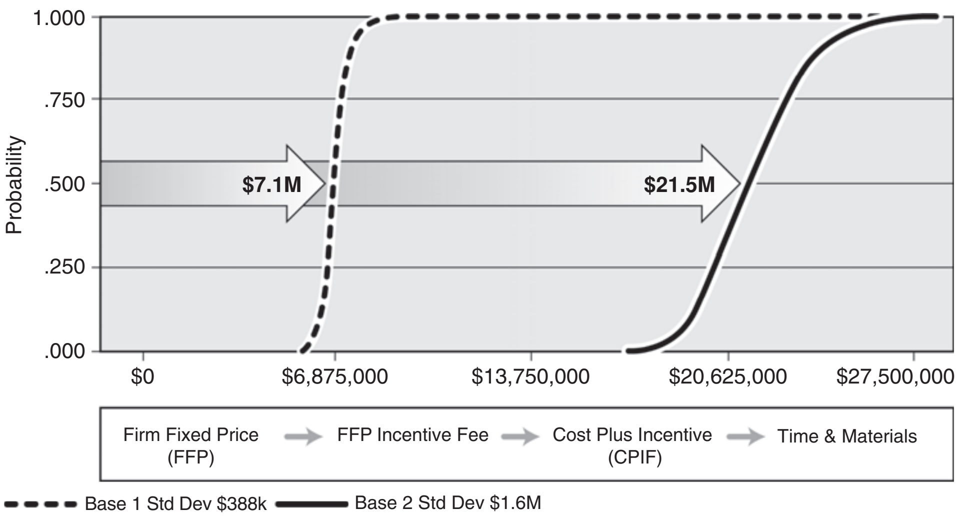

FIGURE 23.6

Probabilistic cost estimating versus contract type.

MAFB and USAF provided a well-defined SOW, which was strengthened by a robust data set in a fully functioning GIS. To further engage the bidding community in the process, a multi-day site visit and contract type training course was developed. All bidders, ACC, MAFB, and the regulatory agency participated, laying the foundation for successful bid development.

The mass of data, along with strong technical evaluations and probabilistic cost estimating prior to SOW development, translated into an appealing solicitation for multiple contractors. Aggressive, innovative, and realistic technical approaches were proposed, and on final award the USAF was able to capitalize on the competitive solicitation. Probabilistic bid forecasts were 7 percent of the actual mean value of bids received, which supported the accuracy and realism of the cost-estimating approach. The result was a successful implementation of a PBC and the opportunity for both the federal government and the contractor to succeed.

23.3 CONCLUSION

There are various ways to meaningfully measure the success of a PBC: potential cost savings, advancement toward site closure, and a realized reduction in life-cycle costs. Surveillance of this process is important. Although the promise of results is more risky in an FFP contract, where results equal payment, in a CPIF contract, surveillance is a beneficial way to verify progress toward meeting the TPOs. For MAFB, a PSVP was developed to identify ways to quantify progress toward the TPOs and a schedule of execution. Capitalizing on the expansive and valuable data set and the GIS developed during the initial stages of PBC crafting, strategies for surveillance were developed that were acceptable to both the USAF and the contractor for verifying performance over time. However, the geostatistics used were acceptable and verified by all stakeholders. The PSVP is still being used to monitor progress toward the TPOs and toward fulfilling the promises made during the contracting stage.

Acknowledgments

The authors of this chapter would like to thank the Air Combat Command, Moody Air Force Base (AFB), and Mrs. Lori Burnam for their support in the successful execution of a Performance Base Contract and their gracious approval to present Moody AFB as a case study.

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PART

Introduction to Sustainability Liability Management

V

Kandi Brown

The environmental and energy priorities emerging from the Obama administration will significantly alter the way we identify and manage environmental liabilities. These priorities include the following:

- Regulation of greenhouse gas (GHG) emissions
- Energy efficiency mandates to achieve a green or low-carbon economy
- Increased use of renewable energy

The path from where we are today to where we want to be will not be an easy one. Use of renewable energy sources such as solar and wind, although reducing carbon emissions, may have a paradoxical, negative impact on the land beneath. As a result of climate change, migration patterns and habitats will shift, infrastructures will require significant reworking, and population demographics will change. Understanding and accounting for uncertainty and its impact on long-term achievement of net environment benefit will require a new approach to decision making and management of liability portfolios. These decisions will require fact-based decision making, from the project level through optimization of multibillion-dollar portfolios. Chapter 24 discusses the common platform of measurement that is used today to track improvements in the USAF environmental restoration portfolio.

Under any pending economic scenario in the United States, carbon emissions and the inherent value of our natural infrastructures in providing ecosystem services, including carbon sequestration, will be a critical component of informed decision making. The Sustainable Asset Accounting System, which is discussed in Chapter 25 and is based on triple-bottom-line accounting principles, provides an excellent example of the kind of tool that can be used to calculate the short- and long-term benefits of projects comprehensively and with consideration of the internalized cost of carbon. Chapter 26 addresses how we can shift our policy-making paradigm so that we can move toward sustainable decisions.

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CHAPTER

24

Portfolio Risk Management Analysis

Kandi Brown, William L. Hall, Robert Barrett, Patrick Gobb

24.1 INTRODUCTION

Although the phrase "portfolio management" is most often used in reference to financial instruments and retirement funds, it can be applied to any use of systematic management across large classes of items belonging to an enterprise or organization. Not only can it be used to optimize assets, but combining it with uncertainty and risk analysis allows management of liabilities and assets as well. Portfolio risk management analysis (PRMA®) increases the probability of successful completion of a business, policy, mission, or sustainability objective. PRMA provides a framework for balancing the outlay of resources (environmental, economic, or social) against sustainability performance metrics.

24.2 PORTFOLIO RISK MANAGEMENT ANALYSIS

PRMA addresses the risk of actions. Risk involves an "exposure to a chance of injury or loss" (Random House, 1966). It is inherent in human health and ecological health assessments, but it can also apply to loss associated with a multitude of factors, such as political stability, financial control, and legal mandates. In the case study presented in this chapter, the focus is on management of environmental liabilities in a portfolio. In that context, PRMA allows enterprises to understand the uncertainty constraints, cost drivers, and limits to liability reduction when moving sites to closure under regulatory mandates, or when constraints are imposed by social or environmental sustainability objectives.

PRMA was developed in direct response to the need to eliminate the *silo effect*—the lack of communication and shared goals due to compartmentalization of departments in an organization. This is a frequent consequence of the narrow focus of an environmental program (e.g., the department for surface water resources not communicating with the department for air pollution). With too narrow a focus, the

DOI: 10.1016/B978-1-85617-797-9.00024-1

solution selected for one problem can create environmental insults more severe than the problem being addressed and opportunities for streamlining are overlooked.

PRMA can be equally powerful in tracking sustainability efforts, renewable energy opportunities, and conservation programs. It is a valuable tool in any program or effort where uncertainty and risk intersect with multiple objectives that should be considered over planning periods of decades, if not centuries.

Uncertainties in an environmental liability portfolio can be driven by lack of data, changing regulatory demands, site location, technology limitations, and so forth. Because uncertainty translates directly to cost, a decision maker must determine how much financial risk transfer or reduction is reasonable and what strategies are needed to produce true (not perceived) risk reduction.

PRMA is strategic and scalable, and it affects all elements of site management. The PRMA process does the following:

- Identifies key indicators of technical, legal, sociopolitical, and mission performance.
- Quantifies the indicators.
- Identifies the primary risk drivers in achieving success.
- Tracks risk over time using one common platform.

A common platform for comparison allows decision outcomes and consequences to be evaluated and tracked across a total portfolio, thus enabling decision makers to:

- Identify the critical uncertainties affecting the portfolio liabilities.
- Select strategic and tactical alternatives for controlling and limiting the impact of uncertainties.
- Establish feedback mechanisms to measure success and adjust liability management approaches.
- Rapidly visualize improvement in the reduction of liabilities.
- Quantify changes in the risk profile.
- Allocate the limited resources of money and personnel across an enterprise.
- Ultimately maximize the return on assets for built and natural infrastructures.

24.3 CASE STUDY: UNITED STATES AIR FORCE

Using PRMA, United States Air Force (USAF) leadership has been able to identify liabilities associated with a broad array of environmental restoration challenges at more than 2,000 sites on 119 installations (or bases) in ten EPA regions. PRMA has been consistently applied since 2006 and is providing valuable insight on site closure trends, best management practices, and future environmental cleanup efforts. The common platform across the USAF's sites provided by PRMA allows a data-driven allocation of resources, an effective means for communication, and a way to bridge the gap that sometimes exists between estimated and actual performance. Yearly, 119 USAF installations are evaluated on the risk faced while achieving technical closeout of their restoration programs and on the cost to complete (CTC) the closeout.

24.3.1 Technical Approach

Technical and cost analyses are carried out independently. Costs are statistically analyzed to determine the CTC, the standard deviation of the cost associated with each installation's program, and the worst-case projection of how much costs may increase with continued expression of the standard deviation (95th-percentile projection).

The *nth* percentile of a ranked set of numbers refers to the value that *n* percent of the numbers are equal to or less than. The 95th percentile refers to the value in the ranked data set that 95 percent of the other values are equal to or less than. Cost statistical analysis and technical analyses determine the risk-driving site at each installation. An installation may contain several sites needing environmental remediation, but the risk-driving site represents the installation's maximum cost and technical risk liability exposure (Figure 24.1).

Technical analysis of the selected USAF bases is probabilistic, assessing a combination of 38 metrics that cover such diverse technical aspects as plume dynamics and risk management (Figure 24.2). Some of the metrics cover mission, legal, and sociopolitical aspects such as public concern, regulatory issues, and contracts in place. An installation's technical profile is a ranking of the risks associated with source, pathway, receptor, and treatment factors.

Source factor rankings consist of metrics that measure the volume and concentration of chemicals released, including soil and groundwater plume size, and confirmed contaminant types. These metrics are assessed using the risk-driving site's data.

Another aspect of the technical profile is the pathway factor ranking—how easily the confirmed contaminant can move through the impacted media to a human or ecological receptor. Components of this ranking include depth to groundwater, precipitation volume and frequency, soil and bedrock characteristics, distance to the base property boundary, surface water transport mechanisms, and site coverage or land cover (e.g., vegetation, impervious surfaces).

Once the source and pathway factors are identified, the receptor factors are ascertained to determine whether the potential pathway of a known release can actually be completed and thus expose a receptor to risk. Receptor factors are ascertained through a complete evaluation of the current and future land use of the impacted area.

The treatment factor rankings are the last component of the technical profile and focus on the difficulty of, and the time required for, achieving a regulatory risk protective standard. In addition to the technical profile, mission, legal, and sociopolitical profiles are developed. These cover the installation as a whole, not specifically the risk-driving site.

The mission profile consists of metrics for encroachment on the mission or constraints on maintaining operations in their current environment. The legal profile focuses on contracts in place governing required restoration activities and on whether contract optimization can be achieved. Finally, the sociopolitical profile looks at the public and regulatory environment in which individual installations

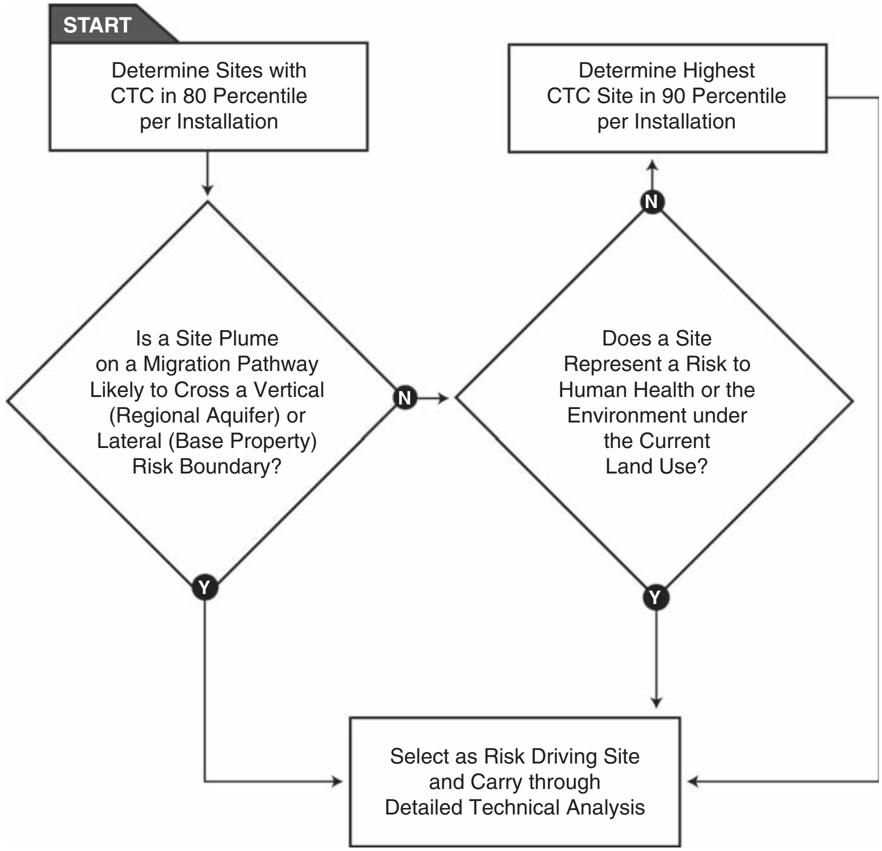


FIGURE 24.1

The risk driving site screening criteria.

operate. The combination of profiles—technical, mission, legal, and sociopolitical—provides a holistic review of an installation's total risk. A series of probabilistic metrics is used in each profile representing varying levels of risk or concern. For example, under the technical profile's source factor ranking, one metric is the size of the groundwater contaminant plume. A plume of 2 acres carries less risk than a plume of greater than 60 acres. In this case, the risk is the technical uncertainty that cleaning up or containing the plume entails.

To quantify the risk of a metric's outcome, each metric is assigned a probability distribution function of values that represent the probability that the metric will pose a relatively high or low risk. This probabilistic assessment uses Monte Carlo computational simulations, which are based on repeated random sampling from a given domain of possible inputs and aggregating the results into the outcomes of greatest probability.

Technical Profile *(Based on Risk Driving Site per Installation)*

Source Factor Ranking

GW Plume Size
Less than 2 acres
2 to 20 acres
20 to 40 acres
40 to 60 acres
>60 acres
Unknown

Soil Plume Size
Less than 2 acres
2 to 5 acres
5 to 10 acres
10 to 20 acres
20 to 40 acres
Unknown

Petroleum Product
No
Possible
Yes—soil and water
Yes—LNAPL
Unknown

VOC
No
Possible
Yes—soil and/or water
Yes—DNAPL
Unknown

Metals
No
Possible
Yes—soil only
Yes—soil and water
Unknown

Exotics (Such as PBC, perchlorate, MEC)
No
Possible
Yes—soil only
Yes—soil and water
Unknown

Pathway Factor Ranking

Soil Permeability
Clay
Sand/Clay
Loam
Sand
Sand/Gravel
Unknown

Depth to GW
>50 ft.
20 to 50 ft.
5 to 20 ft.
<5 ft.

Buffer (Distance to Facility Boundary)
>1000 ft.
500 to 1000
100 to 500
<100
Unknown

Rainfall (Inches/Year)
<15
15–45
>45
Unknown

Likely Surface Water Transport
No
Yes
Unknown

Solution Bedrock (Karst or highly fractured)
No
Yes
Unknown

Site Coverage
Paved from beginning
Currently paved 50–80%
Currently paved 10–50%
Limited pavement 0–10%
Unknown

Perceived Human Health Risk
Under current land use Risk <10e-4
Under current land use Risk >10e-4
Not Available

Perceived Ecological Risk
HQ<10
HQ>10
Not Available

Receptor Factor Ranking

Current Land Use
Industrial
Commercial
Agriculture and Recreational
Mixed Residential
Residential
Unknown

Future Land Use
Industrial
Commercial
Agriculture and Recreational
Mixed Residential
Residential
Unknown

GW Usage
None/Poor Quality
Agriculture
Potential Potable Individual
Potential Potable Municipal
Known Potable Use
Unknown

Deep GW Use
None
Yes (Good Aquitard)
Yes (Poor Aquitard)
Unknown

SW Usage
None/Poor Quality
Recreational
Individual/Subsistance
Fishing or Agriculture
Municipal
Unknown

Habitat
No Critical Habitat
Sensitive
Unknown

Treatment Factor Ranking

Operational System (Subjective Evaluation)
High Value Added
Medium Value Added
Low Value Added
Unknown

Final ROD (Subjective Evaluation)
High Value Added
Medium Value Added
Low Value Added
Unknown

LTM/LTO
5 Years
10 Years
20 Years
>30 Years
Unknown

RAOs
Risk Based
Land Use Appropriate
MCL
Anti-Degradation
Not Documented
Unknown

Site Access
Good
Poor
Unknown

Mission Profile*

Encroachment Issues/Mission Expansion
Low
Medium
High
Unknown

Encroachment Issues/Treatment
Low
Medium
High
Unknown

Encroachment Issues/Natural Resources
Low
Medium
High
Unknown

Missed RIP Dates (Based on Air Staff Tracking Sheet)
0–1
1–3
>3
Unknown

Probability of Meeting 2012 RIP Goal
Likely
Unlikely
Unknown

Legal Profile*

PBC Includes All Environmental Liabilities
Yes
No
Unknown

PBC Objectives Attainable/Probability of Contract Failure Low
Yes
No
Unknown

PBC Objectives Lead to Liability Reduction/Closure
Yes
No
Unknown

Sociopolitical Profile*

Public Concern
Low
Medium
High
Unknown

Off-Base Receptors
No
Yes—Perceived
Yes—True
Unknown

Timeliness of Regulatory Review
3–6 Months
6–12 Months
>1 Year
Not Available

Regulatory Climate
Cooperative
Uncooperative
Unknown

*Based on total installation.

FIGURE 24.2

Technical uncertainty metrics.

Customized probability distribution functions can represent any unique situation. They can be a series of discrete values or they can be continuous or discrete ranges. In the USAF application, the distributions were calculated using a series of discrete values representing the weighting to be applied to individual metric outcomes. Each weighting factor was assigned a probability of occurrence based on the metric being considered.

As mentioned earlier, one of the technical aspects of a contaminated site that may need to be assessed is the size of the contaminant plume in the groundwater. What follows is a discussion of the plume size metric as an example of how metrics were assessed for the USAF portfolio.

For the technical metric of groundwater plume size, six size ranges were considered as potential outcomes:

- Less than 2 acres
- 2 to 20 acres
- 20 to 40 acres
- 40 to 60 acres
- Greater than 60 acres
- Unknown

Generally, each range is given a probability distribution in the discrete rankings of 1 through 5. These ranking values represent the increasing relative risk of technical uncertainty in that metric, so for the groundwater plume metric, a value of 1 represents relatively low risk involved in cleanup or containment. A plume of less than two acres is heavily weighted for a value of 1, whereas one of 60 acres or of an unknown size is heavily weighted for a value of 5, which represents maximum relative technical uncertainty in cleanup or containment.

Figure 24.3 provides an example of the probability distribution for rankings of a groundwater plume of less than 2 acres and one of 2 to 20 acres. As the outcome for less than 2 acres carries the least risk, it is most heavily weighted on the 1 value, with minor weighting to the remaining range as a means of considering uncertainty with the measurement as a whole. The outcome for greater than 60 acres carries significantly more risk and is weighted on the 5 value. When the simulation trials are run and their results are aggregated, a distribution of weighting factors is created showing the likelihood of technical uncertainty or difficulty depending on the size of the plume, including the scenario of an unknown plume size. Unknown results, for any category, carry the greatest risk and are weighted at the maximum rank for the respective metric.

At each step of the USAF simulation process, values assigned to all metrics were combined to form a single base-specific index. Simulations were performed 1,000 times to produce distributions of this index for each base.

The 50th-percentile value of each base-specific index distribution was defined as its total technical uncertainty. To compare the technical uncertainty between bases, the index for each one was normalized by a best-case technical uncertainty

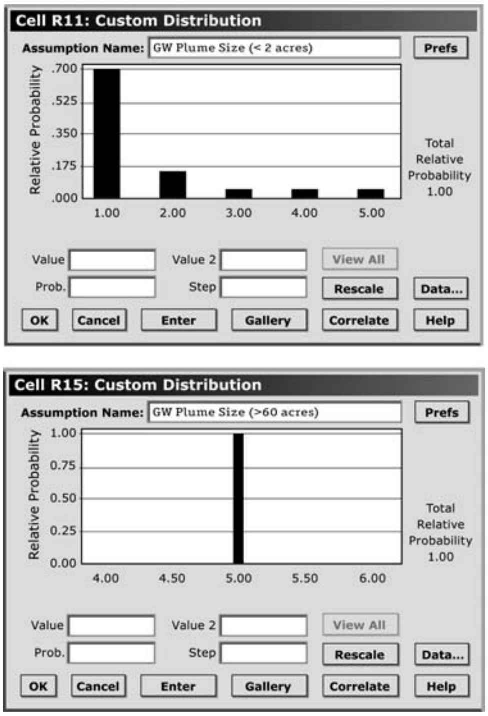


FIGURE 24.3

Customized probability distribution factors.

index calculated by simulating a base with the most favorable technical and socio-political conditions (Figure 24.4).

The results of the technical uncertainty and cost analyses of individual installations were combined to assess and compare the cost and uncertainty relationships between all bases in the USAF portfolio. A Cartesian plane quadrant format was selected as the best illustration of this. To create the quadrants, the x-axis was divided at $15.4 million, the 70th-percentile CTC for all 119 installations; the y-axis was divided at 1.63, the median technical uncertainty result (Figure 24.5) for all installations.

The weighting of individual metrics and their grouping were evaluated. Specifically, both deterministic and probabilistic weightings were applied to the technical profile in total, to the technical, legal, and mission profiles in combination, to individual metrics alone, and to the factors in the EPA's DRASTIC model, which measures groundwater pollution potential (EPA, 1987). DRASTIC factors focus on plume migration and correlate with the technical profile/pathway factors (9 metrics) that represent 25 percent of the 38 metrics the USAF evaluated in the portfolio.

Seven installations were used for the weighting analysis and were selected based on the factors driving their sensitivity analyses, such as records of decision

Base	50th-Percentile Technical Uncertainty	Normalized Technical Uncertainty
A	12.57	1.91
B	11.57	1.76
C	7.43	1.13
Best Case	6.57	1.00

FIGURE 24.4

Technical uncertainty percentile.

(RODs), treatment options, soil plumes, proximity of release to property boundary, and level of surrounding private sector development.

Overall, regardless of the manner in which the weighting was applied, the weighting effect had little to no impact on the installations' quadrant locations. When the weights were applied to all installations in the same manner and quantity, the only change was in the magnitude of the outputs or technical uncertainty results. Because the relative positions in the quadrants did not change, no weighting was applied and all 38 metrics were calculated as equal in weight.

Sensitivity analyses can reveal both the positive and the negative driving forces impacting a technical uncertainty outcome. Comparisons of sensitivity results over time illustrate the rationale for movement across the quadrants (Figure 24.6).

24.4 CONCLUSIONS AND RECOMMENDATIONS

The USAF portfolio results illustrate the technical uncertainty and CTC risk profile for the 119 installations (Figure 24.5). Progression from quadrants 1 and 4 to the more optimal quadrants 2 and 3 is solely driven by USAF CTC input and should reflect dollars expended or cost reduced over time. Progression from quadrants 1 and 2 to quadrants 3 and 4 is driven by improved technical certainty resulting from effective risk-bounding strategy, regulatory negotiations, changes in plume dynamics, land acquisition, and so forth. For optimal status to be achieved (quadrant 3), improvements in technical certainty must be reflected in the program's CTC (Figure 24.6).

The USAF's environmental restoration portfolio represents $2.4 billion in current CTCs. Although it ranges across 39 states in ten EPA regions, Wake Island, Guam, and Washington, D.C., the bulk of its liability is in EPA Regions 4, 8, and 9 (Figure 24.7). The portfolio's standard deviation is being reduced with the growing maturity of the restoration program. Positive correlation in the reduction in technical uncertainty and the reduction in CTCs was demonstrated across 35 percent of the portfolio's installations.

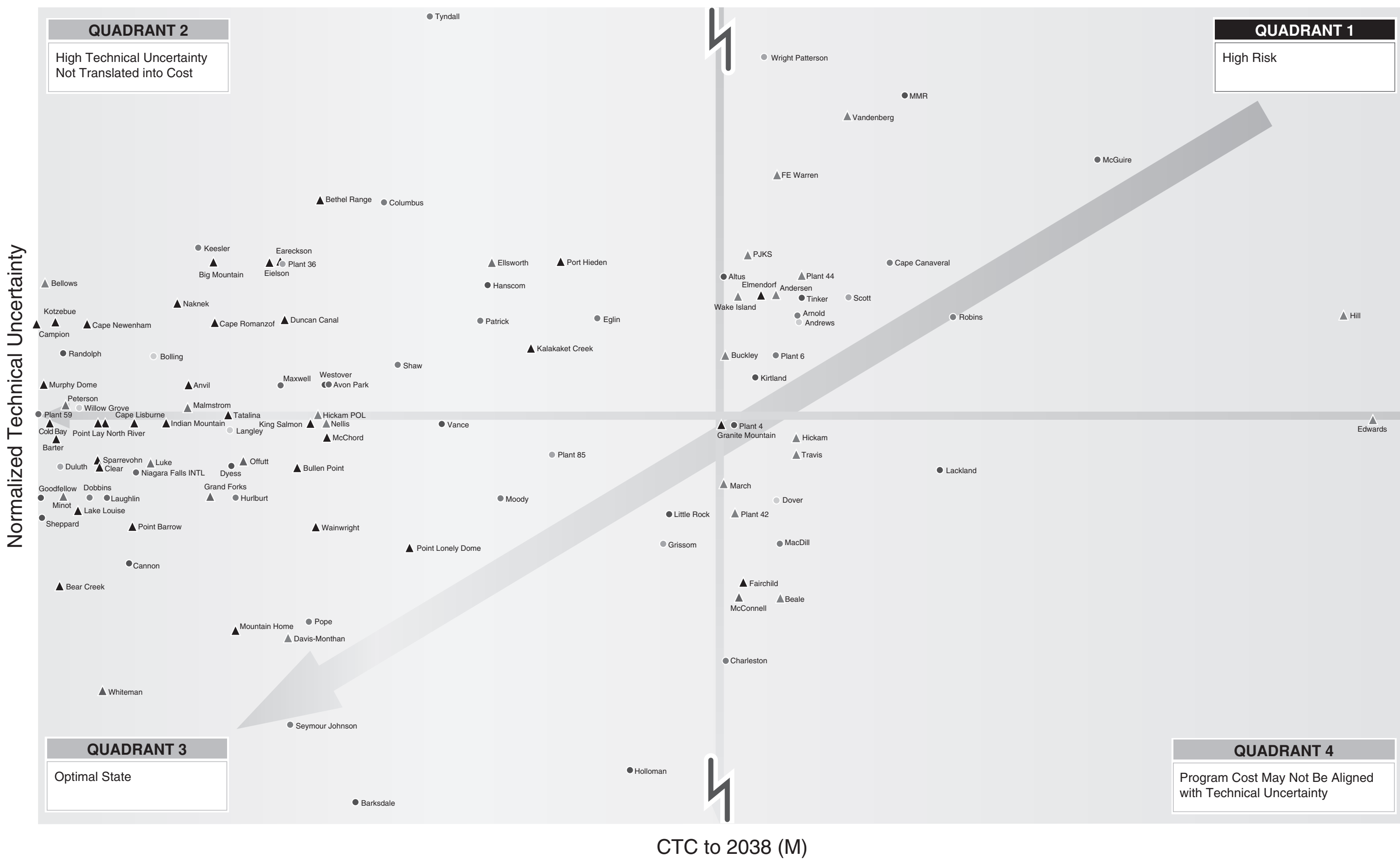


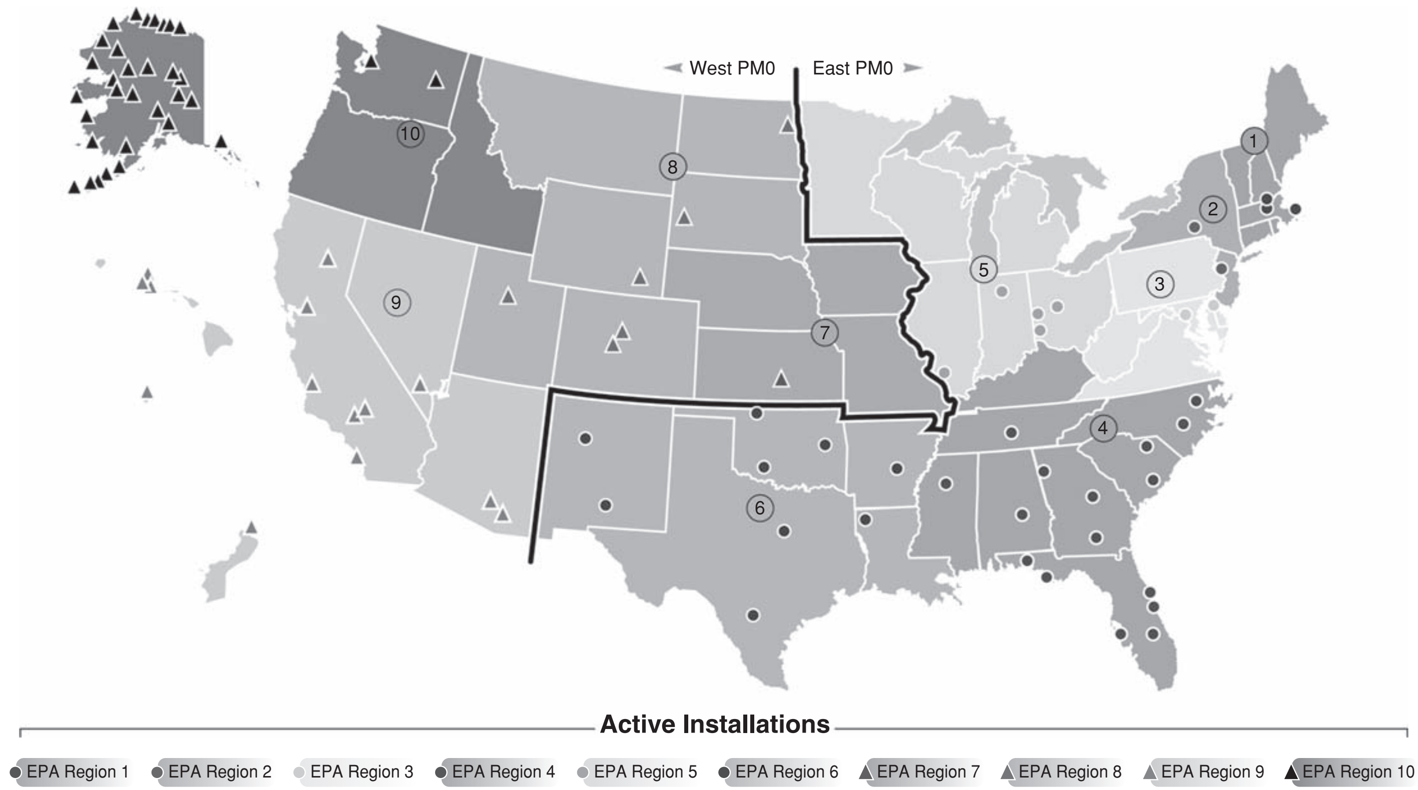
FIGURE 24.5

Air Force profile, November 2007.

Note: Bolded installations have demonstrated positive movement.

FIGURE 24.6

Air Force profile, November 2008.



Note: East PMO is represented by ○, West PMO is represented by △.

FIGURE 24.7

USAF portfolio analysis.

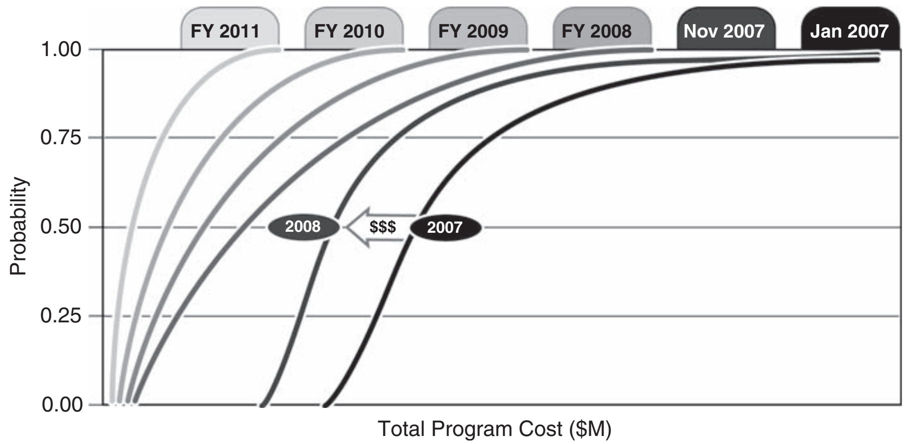


FIGURE 24.8

Program progress to liability closeout.

To make effective executive decisions on risk reduction across a portfolio, the correlation of resources expended to risk reduced must be ascertained and tracked (Figure 24.8). The USAF has a solid system for making this calculation. With consistent, detailed data handling, risk management strategies can be negotiated that are in line with USAF policies and that are legally defensible in subject states and EPA regions.

A primary focus on effective remedial approaches resulting in receptor protection, and consistent with current and reasonably anticipated land use, is paramount. All contract actions must support the technical strategy that ensures liability reduction. The foundation of an overall strategy for site closure and liability reduction is comprehensive risk management consistently applied across the USAF portfolio.

Acknowledgments

The authors of this chapter would like to thank Air Combat Command, Air Force Center for Engineering and the Environment, U.S. Corps of Engineers, and the Air Staff for their support in the development of the tools discussed here.

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CHAPTER

25

The Sustainable Asset Accounting System

Kandi Brown, Kathy Garvin, Adam Saslow, Robert Barrett

The United States Air Force (USAF) recognizes significant equity stemming from both the built and natural infrastructures at installations around the world. Over the next several years, the operation of U.S. installations will be dramatically impacted by the 2020 USAF objectives, Executive Orders mandating reductions in resource demands, and increasing efficiencies (Bush, 2007; Obama, 2009), as well as the pending U.S. carbon cap and trade system currently under debate. To meet these challenges, the holistic, aggressive pursuit of resource leveraging will be required.

It is the large integrated nature of the problem and the many possible solutions that call for a new generation of decision support tools. These tools must accurately reflect the value generated from various solutions to ensure fact-based, data-driven operational decisions required for the long-term, high-impact legal and policy requirements of asset management in this new resource-focused time. Decision tools are needed that link the long-term objectives for natural resource utilization with facility-level budgeting. To meet this need, USAF developed the Sustainable Asset Accounting System™ (SAAS), which uses a traditional business model or balance sheet to quantify equity holistically, considering not only economics but also social impact and environmental stewardship. The SAAS tool forces a process whereby improved resource management is achieved when making multiple, competing operational decisions and provides a common platform from which to quantify the USAF installation's total value when environment, infrastructure, and mission come together.

Overall business accounting that considers sustainability must concern itself with the internal and external costs of social and environmental change. This chapter demonstrates the value of the SAAS that was developed with full recognition of triple-bottom-line (TBL) accounting, which places importance on people, planet, and profit.

DOI: 10.1016/B978-1-85617-797-9.00025-3

25.1 TRIPLE-BOTTOM-LINE ACCOUNTING

An increasing number of companies and governments are adopting or encouraging various forms of TBL accounting. Some U.S. states, including Minnesota and Oregon, are considering legislation permitting corporations to adopt TBL systems. Many businesses have voluntarily adopted TBL as part of their articles of incorporation or by-laws, and there are advocates for state laws creating a special "Sustainable Corporation" class that would grant TBL tax breaks and other business benefits (Filler, 2007).

In Australia, TBL has been adopted as a part of the Western Australian State Sustainability Strategy (Government of Western Australia, 2003). Environment Australia, a program of the Department of the Environment and Heritage, allows environmental indicators to be addressed separately from an organization's balance sheet (Environment Australia, 2003).

The 2003 European Union (EU) Modernisation law, which requires balance sheets to include nonfinancial performance indicators in annual reports, is a step toward TBL accounting. However, many EU companies may be missing the spirit of the law in providing little consistency in what they choose to include in the nonfinancial sections of their balance sheets, and this information is not meaningfully connected to financial data (FEE, 2008).

The United Kingdom's Ministry of Defense (MOD) and the U.S. Army have undertaken sustainable development initiatives with a basis in TBL. As the third largest landowner in the United Kingdom, MOD is working to significantly reduce the 1.9 million metric tons of carbon dioxide emitted each year from its energy use in order to align with the carbon accounts being established by the British government as of March 2009 (Department of Energy and Climate Change, 2008).

The U.S. Army's TBL Plus approach to sustainability reporting considers four major elements: mission, environment, community, and economic benefit. However, because the performance data are reported in multiple units and are not monetized, it is only appropriate for sustainability reporting, not accounting.

Although it has become a popular concept, corporations are not currently implementing TBL accounting in their balance sheets. For example, a search for the phrase "Triple Bottom Line" in ProQuest's business information database, ABI/INFORM®, yielded more than 500 results. However, although a review of the 150 most recent articles provided interesting analyses of how the TBL general concept had been adopted, none of them discussed any organizations' actual balance sheets.

Dozens of sustainability reports that received A or A+ ratings from the Global Reporting Initiative (GRI) were reviewed. The companies whose GRI ratings indicated that they had the highest level of sustainability reporting had not incorporated environmental indicators into their actual balance sheets. Target companies' annual report filings with the Securities and Exchange Commission

(SEC) also revealed that environmental and social indicators are reported under the separate heading “Nonfinancial Statements.”

Sustainability reporting and progress indicator tracking are vital, but they do not provide a comprehensive view of a corporation’s or organization’s well-being. Specifically, individual progress indicators lose the cross-references or eco-efficiencies that are the hallmark of healthy systems—especially when standardized to a universally comparable unit and/or monetized (Minnesota EQB, 2000; Schaltegger et al., 2006). For economic policy makers and planners to understand the impact of economic policies on natural resources and carrying capacity, social and environmental considerations must be integrated into economic decisions, not tracked separately or kept in satellite accounts (Minnesota EQB, 2000).

Progress is being made in sustainability reporting, and GRI is now promulgating generally accepted standards, but the need for TBL accounting standards remains. The recent global recession may accelerate the use of more holistic accounting practices to avoid reliance on short-term decision making driven solely by economic factors. The complexity of TBL accounting cannot be overlooked. As stated by Henriques and Richardson (2004):

> *Much progress has been achieved in understanding the TBL of sustainable development since the early 1990s. Understanding the economic bottom line, as opposed to the purely financial, is an essential pre-condition to achieving sustainability. However, understanding and measuring the interactions between the economic and the social and between the economic and the environmental bottom lines remain the key challenges.*

25.2 THE SUSTAINABLE ASSET ACCOUNTING SYSTEM

The USAF SAAS was created to demonstrate the business case for sustainable asset management by considering the externalized and internalized cost of actions in terms of carbon as well as environmental and social impact. The equity of built and natural infrastructures was analyzed to develop the SAAS, which was pilot-tested in 2008 at Barksdale Air Force Base (BAFB) in Louisiana.

The SAAS considers the economic values of property, plant, and equipment across all functional units that are visualized in a geographic information system (GIS). It also considers the environmental and social values that accrue across an entire base, thus providing a baseline balance sheet equity or net worth against which changes in various programs can be quantified in income statements, balance sheets, and other tracking systems. In this way, the impact of changes on an asset’s long-term value can be monetized.

The SAAS was constructed from a baseline chart of accounts, which documented expense, revenue, asset, and liability accounts. The values assigned to the chart were monetized metrics tied to the USAF objectives for energy and water conservation.

These metrics were housed in a Microsoft Office Excel spreadsheet with an Oracle Crystal Ball add-in, and linked to the GIS for 3D/4D visualization.

In the BAFB application, sustainability was defined as the degree to which value out meets or exceeds value in; in other words, a sustainable system has stable or increasing equity over time. This definition supports the intergenerational definition of the 1987 Brundtland Commission: "Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987).

Only a certain amount of consumption, or expense, can be financed during a given period of time while maintaining the wealth, or equity, of an entity at the original level (Azqueta, 2007). The SAAS illustrates the maximum amount the USAF can consume during a period of time and remain as well off at the end of that time as at the beginning, or baseline. However, defining sustainability as stable or increasing equity is valid only if all components of sustainability performance are considered—economic, environmental, and social (Schaltegger et al., 2006). Through this lens, use of TBL accounting was essential in the accurate creation of the SAAS.

The *DoD Natural Infrastructure Asset Valuation Guide* (2008) clearly adopts a TBL philosophy. It defines total economic value as the sum of the direct, indirect, option, and nonuse values of all services an asset provides. Total value is defined as "incorporation of the three main types of value: economic, ecological, and sociocultural," which, the guide goes on to state, "are not commensurate; that is, they cannot all be expressed with one common unit of measure and totaled up. Qualitative approaches are often needed to deal with these very different types of value."

In the past, the DoD steered away from monetary valuation of natural infrastructure because of the philosophical and methodological obstacles it could present (DoD, 2008). Monetary valuation had been criticized for being difficult, frequently time-consuming, and expensive to determine, as well as subject to substantial critique. However, the SAAS presents a way to overcome such obstacles by providing:

- A framework for selecting and calculating monetary valuations for factors (subcategories) that impact the bottom line.
- A process for representing both deterministic and nondeterministic numbers as ranges, weighted and measured for uncertainty to produce a value that incorporates professional judgment, site knowledge, and the ability to address projected changes over time.
- An inventory of baseline conditions for quickly performing relative comparative analysis (at any level of the organization) or before and after proposed actions.

The monetary valuation approach was selected for the SAAS for a number of reasons. Chief among these was that dollars are a widely accepted and understood unit of measurement, and the majority of data points selected for analysis, such as the market value for renewable energy sources, can easily be converted to U.S. dollars (USD). Conversions and algorithms were developed to be transparent with easily manipulated variables (i.e., user friendly) when applying site-specific parameters and converting values to USD.

In the BAFB chart of accounts, each accounting element was quantified, the source of the data documented, and the data organized into traditional accounting categories: revenue, expenses, assets, and liabilities. The raw data units were then evaluated. Since the bulk of the raw data was entered in USD, it was determined that all units would be standardized to USD. Once the variances of the standardization were quantified, the final simulated values were calculated and were represented as Air Force dollars (AF$) to distinguish between deterministic and simulated values.

Because dollars are an easily recognized unit of measure, they create a more robust system. In general, the more abstract the unit of measure, the easier it is to confuse, game, and destabilize the evaluation system. The SAAS was developed as a tool to express total value in one common unit. It incorporated all economic, ecological, and sociocultural activities at BAFB and categorized them into revenues, expenses, assets, and liabilities associated with both the built and natural infrastructures.

In total, the SAAS is comprised of the following:

- Database management for account inventory and tracking
- Current and predicted recurrent utility costs
- Valuation of credits and offsets
- Capital and O&M future outlay estimates
- Remote-sensing input for land cover satellite imagery analysis
- DeNitrification-DeComposition (DNDC) modeling for greenhouse gas flux and offset project tracking
- Carbon emissions inventory using Inter-Governmental Panel for Climate Change (IPCC) protocol
- Ecosystem services valuation per DoD Natural Infrastructure Valuation Guidance (DoD 2008)
- Archaeological and cultural services valuation
- GIS visualization
- Triple Bottom Line accounting system as a common platform for monetization and forecasting

The general technical approach to the SAAS (summarized as follows) is applicable to any private or public sector installation.

- GIS development and data acquisition:
  - Obtain data from all facets of the operation.
  - Acquire satellite imagery over time intervals that reveal major changes in the built or natural infrastructure.
  - Create a GIS to rapidly analyze the data collected.
  - Establish the boundaries of the organization being evaluated using available data.

- Populate the revenue, expense, asset, and liability categories in the chart of accounts following generally accepted accounting principles:
  - Establish ecosystem revenue streams per the DoD Natural Infrastructure Asset Valuation Guide.
  - Establish greenhouse gas (GHG) flux using methods that are accepted by the Chicago Climate Exchange (CCX) or the European Climate Exchange (ECX), and that are most applicable to the natural infrastructure composition of the installation (see Chapter 19 for a discussion of GHG flux modeling).
  - Internalize the cost of carbon by calculating the tonnes emitted and monetizing the amount as an expense.
- Unit standardization:
  - Determine the unit in which the majority of raw data is delivered.
  - Standardize all data to that unit.
- Probabilistic determination of equity and profit:
  - Capture the uncertainty of the unit standardization and potential monetary range using utility theory.
  - Employ a predictive market to quantify stakeholder confidence in the conversions, if needed.
- Modeling of changes in profit and equity using income statements:
  - List assumptions.
  - Use journal entries to track projected changes in the chart of accounts.
  - Maintain double-entry accounting standards.
- Sensitivity analysis:
  - Conduct sensitivity analysis to determine the balance sheet risk drivers.
  - Calculate DuPont ratios for return on asset (ROA), return on investment (ROI), and leverage ratio.
  - Develop a strategy to reduce risk drivers to stabilize or increase equity and maximize the value derived from the asset.

To the extent possible, the SAAS used generally accepted accounting principles to value, assess, and compare baseline conditions at BAFB as well as impacts to the baseline from individual projects or policy actions. Following the guidance outlined in the *DoD NI Valuation Guide* (2008) for the preferred asset management process, the SAAS performs the following steps:

Step 1: Inventory and assess assets. Prior to the assessment of proposed actions, both built and natural infrastructure is inventoried in the chart of accounts.

Step 2: Identify problems and opportunities. By developing an income statement for a proposed action that could impact the bottom line, potential problems and opportunities are identified via sensitivity analysis.

Step 3: Identify and analyze options. Several proposed actions may be entered quickly into the SAAS to compare the relative differences to the bottom line and analyze the key drivers contributing to the revenue, expense, asset, or liability accounts.

Step 4: Take action. Once the comparison is completed and the preferred alternative is selected, best practices and sustainable opportunities may be realized.

25.3 THE SAAS CHART OF ACCOUNTS

As mentioned previously, the SAAS was constructed from a baseline chart of accounts, that documented expense, revenue, asset, and liability accounts. The values assigned to the chart were monetized metrics tied to the USAF objectives for energy and water conservation. These metrics were housed in a Microsoft Office Excel spreadsheet with an Oracle Crystal Ball add-in, and were linked to the GIS for 3D/4D visualization. The following subsections detail the SAAS chart of accounts as summarized in Figures 25.1(a) through 25.1(d).

25.3.1 Revenue/Pseudo-Revenue Value Account

Revenues are generally defined as income from the ordinary activities of a particular corporation, company, partnership, or sole proprietorship. In the SAAS, the pseudo-revenue value account includes monetized value streams from mission as well as ecosystem services, allowing the valuation and tracking of services for which cash currency is not actually received or realized. The SAAS tracks the following seven categories of revenue accounts:

- Mission services
- Energy sources
- Ecosystem services
- Transportation
- Lease/rent
- Social
- Other

Sensitivity analysis indicates that the primary revenue factors for military installations are mission services and the social component of value of jobs created. This fact demonstrates the value of military installations not only in the communities in which they operate but also in the United States as a whole.

Mission Services

The mission services revenue stream is made up of open land, and military personnel and infrastructure. Open land revenue was determined based on the value of land surrounding the airfield that facilitates execution of the mission. The acreage of open land was calculated from the total area footprint, including the clear, noise (dB), accident, and jettison zones (11,803 acres). Given the current use of these

Type	Category	Subcategory	Account Detail	Raw Unit 2008/2009	Conversion Algorithm/Documentation
Revenue	Mission Services	Homeland Security	Open Land	acres	Acres for airfield operation (clear zone, db, accident, jettison without overlap) × market value ranging from residential to commercial.
Revenue	Mission Services	Homeland Security	Military Personnel and Infrastructure	USD	Military personnel salaries plus MilCon for military support only discounted over 25 years.
Revenue	Ecosystem Services	Direct Use Services	Recreation	USD	Value ranged from amount Base collects per year to NRLAM study estimate. NRLAM willingness to pay survey based on other regional resources/benefit transfer indicates that the potential fees collected could be as much as $2,800,000/yr if all recreational assets were open to the public (golf course excluded from the evaluation and fee-collection estimate).
Revenue	Ecosystem Services	Direct Use Services	Food Supply (on base gardens)	acres	Market price for volume of food produced with land intact minus market price for volume of food produced with land impacted/year. Base provides 30–40 acres on base for gardens for 20–25 households.
Revenue	Ecosystem Services	Indirect Use Services	Carbon Sequestration (upland forest)	Total GHG (CO_2 equiv)—Metric tons	Tons sequestered/year × market value on Chicago Climate Exchange. This service is carried as a revenue stream only. The long-term value of sequesting is carried in the value of the forest itself, which is an asset.
Revenue	Ecosystem Services	Indirect Use Services	Carbon Sequestration (wetlands)	Total GHG (CO_2 equiv)—Metric tons	Tons sequestered/year × market value on Chicago Climate Exchange. This service is carried as a revenue stream only. The long-term value of sequesting is carried in the value of the wetland itself, which is an asset.
Revenue	Lease/Rent Revenue	Lease/Rent Revenue	Chase Bank	USD	None
Revenue	Social Revenue	Social Revenue	Value of Jobs Created	USD	None
Revenue	Social Revenue	Social Revenue	Recreational and Pet Facilities	USD	None
Revenue	Other Revenue	Other Revenue	Waste Recycling	tons	Tons × disposal cost avoidance.
Revenue	Other Revenue	Other Revenue	Timber Sales	USD	Varying volume at market value.

FIGURE 25.1(a)

Chart of Accounts for the Sustainable Asset Accounting System.

Type	Category	Subcategory	Account Detail	Raw Unit 2008/2009	Conversion Algorithm/Documentation
Expenses	Carbon Costs	Carbon Costs	E85	Total Tonnes CO_2	Lost trading potential on the Chicago exchange from carbon emission.
Expenses	Carbon Costs	Carbon Costs	Electricity	Total Tonnes CO_2	Lost trading potential on the Chicago exchange from carbon emission.
Expenses	Carbon Costs	Carbon Costs	Natural Gas	Total Tonnes CO_2	Lost trading potential on the Chicago exchange from carbon emission.
Expenses	Land and Facility Management Costs	Land and Facility Management Costs	Grounds Maintenance	USD	None
Expenses	Land and Facility Management Costs	Land and Facility Management Costs	Custodial	USD	None
Expenses	Land and Facility Management Costs	Land and Facility Management Costs	Refuse	USD	None. This contract also includes the cost of the recycling program.
Expenses	Land and Facility Management Costs	Land and Facility Management Costs	Conservation Program	USD	None
Expenses	Land and Facility Management Costs	Misc Service Contracts	Port-a-pottie	USD	None
Expenses	Land and Facility Management Costs	Misc Service Contracts	Elevator Maintenance	USD	None
Expenses	Land and Facility Management Costs	Misc Service Contracts	Grease Trap Cleaning	USD	None
Expenses	Land and Facility Management Costs	Misc Service Contracts	Kitchen Exhaust System Cleaning	USD	None
Expenses	Land and Facility Management Costs	Misc Service Contracts	Oil, Water Separate Grit Chamber Services	USD	None
Expenses	Installation Operations	Installation Operations	Annual Expenditures	USD	None
Expenses	Installation Operations	Installation Operations	Salary—Personnel	USD	None
Expenses	Installation Operations	Installation Operations	MILCON	USD	None
Expenses	Natural Resource Consumption	Natural Resource Consumption	Forestry Consumption	Metric tons CO_2 emitted	Lost trading potential on the Chicago exchange from carbon emission.
Expenses	Potential Savings	Potential Savings	Natural Gas	USD	Potential savings represents the amount Barksdale could save by executing their option for a reduced purchase price of natural gas produced on East Reservation.
Expenses	Energy/Fuel Costs	Traditional Power Sources	Electricity	USD	None
Expenses	Energy/Fuel Costs	Traditional Power Sources	Natural Gas	USD	None
Expenses	Energy/Fuel Costs	Fuel	Mogas	gallons	Quantity × Standard Pricing
Expenses	Energy/Fuel Costs	Fuel	Diesel	gallons	Quantity × Standard Pricing
Expenses	Energy/Fuel Costs	Fuel	JP8	gallons	Quantity × Standard Pricing

FIGURE 25.1(b)

Type	Category	Subcategory	Account Detail	Raw Unit 2008/2009	Conversion Algorithm/Documentation
Expenses	Energy/Fuel Costs	Fuel	Biodiesel	gallons	Quantity × Standard Pricing
Expenses	Energy/Fuel Costs	Fuel	E85	gallons	Quantity × Standard Pricing
Expenses	Water Management Costs	Water Management Costs	Water	USD	None
Expenses	Waste Management Costs	Waste Management Costs	Sewage	USD	None
Expenses	Waste Management Costs	Waste Management Costs	Solid Waste Disposed	tons	Volume of on-base waste disposal in soil (landfill) × cost of landfill off base. No current landfilling on base.
Expenses	Waste Management Costs	Waste Management Costs	ERP Cost Incurred	USD	None
Expenses	Waste Management Costs	Waste Management Costs	MMRP Restoration Cost Incurred	USD	None
Expenses	Waste Management Costs	Waste Management Costs	Compliance	USD	None
Expenses	Waste Management Costs	Waste Management Costs	P2 Program	USD	None
Expenses	Permit Fees and Fines	Fees	Drinking Water	USD	Permit cost divided by renewal timing yearly.
Expenses	Permit Fees and Fines	Fees	UST	USD	Permit cost divided by renewal timing yearly.
Expenses	Permit Fees and Fines	Fees	Air	USD	Permit cost divided by renewal timing once per 5 years.
Expenses	Permit Fees and Fines	Fees	Stormwater	USD	Permit cost divided by renewal timing yearly.
Expenses	Permit Fees and Fines	Fees	Sanitary	USD	Permit cost divided by renewal timing yearly.
Expenses	Permit Fees and Fines	Fines	Drinking Water	USD	None
Expenses	Permit Fees and Fines	Fines	UST	USD	None
Expenses	Permit Fees and Fines	Fines	Air	USD	None
Expenses	Permit Fees and Fines	Fines	Stormwater	USD	None
Expenses	Permit Fees and Fines	Fines	Sanitary	USD	None
Expenses	Carbon Costs	Carbon Costs	Mogas	Total Tonnes CO_2	Lost trading potential on the Chicago exchange from carbon emission.
Expenses	Carbon Costs	Carbon Costs	Diesel	Total Tonnes CO_2	Lost trading potential on the Chicago exchange from carbon emission.
Expenses	Carbon Costs	Carbon Costs	JP8	Total Tonnes CO_2	Lost trading potential on the Chicago exchange from carbon emission.
Expenses	Carbon Costs	Carbon Costs	Biodiesel	Total Tonnes CO_2	Lost trading potential on the Chicago exchange from carbon emission.

FIGURE 25.1(c)

Type	Category	Subcategory	Account Detail	Raw Unit 2008/2009	Conversion Algorithm/Documentation
Assets	Fixed Assets	Installation Lands Owned	Impervious (Transportation, Buildings)	acres	Acreage × Market Value a Blend of Commercial and Industrial
Assets	Fixed Assets	Installation Lands Owned	Grassland/Herbaceous	acres	Acreage × Market Value Residential
Assets	Fixed Assets	Installation Lands Owned	Coniferous Forest (clear-cut succession)	acres	Acreage × Market Value Residential
Assets	Fixed Assets	Installation Lands Owned	Deciduous Forest (upland and lowland deciduous, transitional)	acres	Acreage × Market Value Residential
Assets	Fixed Assets	Installation Lands Owned	Mixed Forest	acres	Acreage × Market Value Residential
Assets	Fixed Assets	Installation Lands Owned	Bare Rock/Sand/Clay	acres	Acreage × Market Value Residential
Assets	Fixed Assets	Installation Lands Owned	Woody Wetlands	acres	Acreage × Estimated 1/2 Market Value Residential
Assets	Fixed Assets	Installation Lands Owned	Emergent Herbaceous Wetlands	acres	Acreage × Estimated 1/2 Market Value Residential
Assets	Fixed Assets	Installation Lands Owned	Urban Forest	USD	None
Assets	Fixed Assets	Installation Lands Owned	Golf Course	Greens	This is the value of the golf course infrastructure, not the recreational fee of use. For Barksdale the expense of operation and the revenue generated are maintained separate from AF accounts. However, the AF owns the lands and the value of the land development.
Assets	Fixed Assets	Owned Land Leased	Housing Lands	acres	Part of privatization of housing.
Assets	Fixed Assets	Installation Water Resources	Water Storage Capacity	gallons	Market price of water.
Assets	Fixed Assets	Plant and Equipment	Plant Replacement Costs	USD	None
Assets	Other Assets	Other Assets	Community Benevolence	USD	Economic Impact as a measure of Community Goodwill.
Assets	Other Assets	Misc	ERP Capital	USD	None
Liabilities	Current Liabilities	Restoration	ERP Cost to Complete to Closure	USD	None
Liabilities	Current Liabilities	Restoration	MMRP Restoration Cost to Complete to Closure	USD	None
Liabilities	Long-Term Liabilities	Fixed Property, Buildings, and Infrastructure	Vacant/Condemned Buildings	USD	None

FIGURE 25.1(d)

areas, the acreage was monetized based on USD/acre value ranging from commercial to residential with a simulated probabilistic AF$.

Military personnel and infrastructure revenue was valued based on the assumption that all military personnel and pending infrastructure development that solely support the mission in execution and/or logistics generate a dollar-for-dollar service-to-cost ratio. As a result, this revenue stream was quantified by adding the 2008 Economic Impact Analysis (EIA) military salaries with the Military Construction (MilCon) prioritized list of mission-related projects.

Energy Sources

The energy sources revenue stream comprises placeholder accounts for a variety of renewable energy projects such as hydropower, solar, wind, biofuels, geothermal, and gas-fired fuel cell (note that no placeholder accounts are listed in Figure 25.1). As of 2008, no renewable energy projects were under way at the base, although gas-fired fuel cell and geothermal projects are slated for the future. These value streams were included in the income statements to forecast the value of various energy-related efforts.

Ecosystem Services

The market appraisal method was used to monetize the ecosystem services benefiting the base, whenever possible. In instances where market prices were not available, other methods were applied—for example, replacement cost or benefit transfer. At all times, the least complex method was selected to facilitate transparency in the SAAS and to minimize unnecessary derivation of relative numbers. Because of the scope and magnitude of this project, there were no empirical studies, such as survey development for "willingness to pay" data.

Existing data were used to the greatest extent possible, and minimum and maximum ranges were then weighted based on uncertainty in order to leverage information gained and services valuated in previous USAF-wide and BAFB studies. The subsections that follow describe the methodology used to value each ecosystem was service selected for inclusion in the chart of accounts.

Water Resources Provided to the Community

This ecosystem service revenue stream was valuated by the market appraisal method. Cost per gallon of drinking water supplied by the local water department was used to develop an algorithm of dollar per gallon of drinking water to valuate any water supplied from base resources. No range was applied to this value; the number was directly transferred based on the local market price of drinking water.

Food Supply (On-Base Gardens)

This ecosystem service revenue stream was valuated by the cost avoidance, or substitute cost, method for the equivalent amount of produce if it were delivered on base. As produce is a marketed commodity, minimum and maximum values were assigned according to the transferred cost of the market price for the equivalent amount of produce.

A multiplier was also used in the minimum and maximum calculations to account for productivity fluctuations throughout a seasonal year (e.g., monthly costs of produce delivery were calculated based on a 6-month, rather than a 12-month, interval under the assumption that costs would not be equally avoided throughout the duration of an entire year, based on productivity fluctuations).

Recreational Services

A combination of methods, including market appraisal and benefit transfer, was used to value the recreational ecosystem services benefiting the base. A range of numbers was given to this value, with the minimum value being the actual (direct) market value of fees and other revenue presently received by BAFB for natural infrastructure–related recreational services provided on base. The upper limit, or maximum value, was that for all natural infrastructure-related recreational resources, derived from the 2004 BAFB Natural Resource Liability Asset Management study, using benefit transfer for similar recreational resources located elsewhere in the United States.

These services included fishing, motorized boating, camping, picnicking, wildlife observation, horseback riding, and big-game, small-game, and waterfowl hunting. The range was weighted heavily toward actual revenue currently generated on base from recreational resources to account for the uncertainty typically associated with the benefit transfer method.

Stormwater Runoff/Water Purification

These ecosystem services were valuated using the replacement cost method. Values were based on the actual cost of labor and construction for a comparable engineered water filtration system. For BAFB, this included construction of a retention basin (for surface water filtration of stormwater runoff) and a wastewater treatment plant (for water discharged and subsequently filtered by the wetland). These costs were broken down into the number of dollars per day per gallon of water treated.

Waste Decomposition and Detoxification

This ecosystem service was valuated with the market appraisal and replacement cost methods. Market prices for the treatment and disposal of nonhazardous wastes were used to determine the cost per day per ton for hauling and storing wastes on base. Minimum and maximum values were collected from local service providers. Landfill capacity (in tonnage) was the basis for calculating the value of waste decomposition benefiting BAFB.

Carbon Sequestration and Carbon Credit Accrual

Both carbon sequestration and carbon credits are now accepted and traded market commodities. Therefore, the direct market value of carbon sequestration potential per metric ton (MT) and carbon credits were used to valuate this ecosystem service. Minimum and maximum ranges were applied using the annual minimum and maximum of the CCX. The model selected for base greenhouse gas flux analysis was DNDC, which was developed for both agricultural and forested upland and wetlands. (DNDC was described in detail in Chapter 19.)

Transportation

The transportation revenue stream was a placeholder to capture any future mass transit efforts BAFB may undertake.

Lease/Rent

The lease/rent revenue stream captured the currency from the lease or rental of base facilities. These included gas leases, rent received from Chase Bank, and miscellaneous reimbursable programs. In 2008, the rent from Chase Bank provided the only revenue stream in this category.

Social Revenue

The social revenue stream accounted for the value of jobs created, as documented in the 2008 EIA, as well as the recreational and pet facilities provided on base that enhance quality of life. Revenue from these facilities was quantified on the basis of fees received per year.

Other

Other revenue streams included waste recycling, timber sales, radio frequency leases, water recycling/reuse, construction debris recycling, predemolition salvaging, and landfill tipping fees. The probabilistic, simulated AF$ for waste recycling was based on tonnes of solid waste recycled in 2008 multiplied by the range in cost for landfilling. Timber sales were probabilistically valued based on the historic range of revenue generated per year. Placeholders for the remaining subcategories were provided in the event that recycling and salvage projects increased. A placeholder for the future leasing of excess radio frequencies was also provided.

25.3.2 Expenses

An expense is defined as an event in which an asset is used up or in which a liability is incurred. The SAAS currently tracks twelve expense categories, with room for expansion as additional accounts are identified. The categories and subcategories are as follows:

- Energy/fuel costs
- Water management costs
- Waste management costs

- Permit fees and fines
- Carbon costs
- Land
- Environmental insurance costs
- Installation operations
- Natural resource consumption
- Social costs
- Other costs
- Potential savings

Sensitivity analysis indicates that the primary expense categories are installation operations, followed by energy and fuel costs. This fact supports the USAF strategic objectives of conservation and reduction in physical plant.

Energy Costs

Energy consumption was provided in both volume and USD values by the base. Fuel costs were calculated using volumes provided by the base multiplied by the pricing provided in the UFC-3-701-08 DoD 2008 *Facilities Pricing Guide*.

Water and Waste Management Costs and Permit Fees and Fines

Deterministic costs for water and waste management were provided by the USAF. Permit fees were probabilistically determined assuming they could be obtained for 90 to 100 percent of the current purchase price. Fines were set at $0 based on 2008 actuals; this value was supported by the lack of past violations.

Carbon Costs

The SAAS quantified carbon dioxide emission values as expenses to internalize the cost of carbon emissions. This information was also used to numerically compare against various GHG offsets or base-wide assets with sequestering capacity, in order to understand and quantify the net effects. The GHG emissions for consumption of varying energy types (natural gas, electricity, fossil fuels) were based on the IPCC Guideline conversion factors.

Land

Land and facility management costs were taken from the deterministic contract values for 2008 for grounds maintenance, custodial services, refuse removal, and miscellaneous services. Placeholders for road maintenance and archaeological site preservation were also included.

Environmental Insurance Costs

An account for environmental insurance costs was included in the event that environmental insurance for environmental restoration program (ERP) or military munitions response program (MMRP) restoration efforts was obtained separately, rather than through the executing contractor.

Installation Operations

Installation operations represent the primary expense account in the SAAS chart of accounts. BAFB annual expenditures and salary components were deterministically entered from the 2008 EIA. The military construction component was the total of programmed projects, linearly discounted over a 25-year period.

Natural Resource Consumption

In TBL accounting, the consumption of natural or ecological assets must be accounted for as an impact to the bottom line. Therefore, accounts for BAFB's consumption of natural gas, minerals, forestry, and water were provided. Although natural gas is extracted from the base, the USAF does not own the mineral rights to it and as a result could not account for the loss of this resource in the SAAS. The base does not use groundwater as a drinking water or irrigation source. As of 2008, it consumes forestry at 80 acres, or about 1 percent, per year. The value of this forest was calculated from the probabilistic loss of carbon sequestration trading potential on the CCX.

Social and Other Expenses

No social or other expenses were identified. However, a negative expense stream of significant value was recognized. As of 2008, the base was paying approximately $1 per 100 cubic feet (cf) for natural gas. Based on its gas lease agreement with the Bureau of Land Management (BLM), it has the option to purchase natural gas directly from the wellhead at 50 percent of the wellhead cost ($0.8/100 cf), or $0.4/100 cf (Energy Information Administration, 2008). The simulated AF$ for this category represented the potential savings range that the lease option could provide annually, assuming an equal probability of utilizing the contract fully (100 percent) or not at all (0 percent).

25.3.3 Assets

Assets are defined as everything of value owned by a person or a company. The three primary categories of assets tracked by the SAAS are (1) current, (2) fixed, and (3) other. Sensitivity analysis indicated plant replacement costs as the principle fixed asset.

Current Assets

BAFB's 2008 assets included cash or currency from additional funding, receipt of liquidated damages inherent in ongoing contracts, and third-party liability reimbursements for environmental impacts. Annual permits can also be valued as an asset if they are entered into voluntarily and increase the efficiency and/or stability of operation. Required permits are not considered assets but are viewed as a tool for appropriate operation. An accounts-receivable placeholder was added to the SAAS chart of accounts to capture any future carbon-trading accruals. No prepaid expenses were recognized during this tracking period.

Fixed Assets

Base fixed assets included installation lands, leases and easements, water resources, and plant replacements costs. Installation lands were quantified via satellite imagery to detail the land cover. (See Chapter 13 for a detailed discussion of remote-sensing technology.) They were then valued using the Concept Opportunity Study fair market value ranges for land uses. A deterministic value for urban forest was captured, as well as the probabilistic value for golf course infrastructure. Accounts for lands leased and otherwise managed were also included.

The value of the base water supply was determined by multiplying the volume of water stored by the water's market value. Plant replacement cost captured the primary asset value of the installation's built infrastructure. Other assets such as cultural, environmental management, and community benevolence were assessed as well. The social component of community benevolence was monetized using the value of economic impact to the community (EIA 2008).

Other Assets

Accounts for miscellaneous assets such as capacities, base-operated utilities, ERP capital equipment, and so forth, were tracked.

25.3.4 Liabilities

Liabilities are defined as an entity's obligation arising from past transactions or events, the settlement of which may result in the transfer or use of assets, the provision of services, or any other economic benefits in the future. The primary liability recognized on the BAFB balance sheet was MMRP restoration. Its 2008 estimate was considered conservative based on the maturity of the program and the potential that not all costs had been fully identified. Other long-term liabilities included the cost for building demolition as well as any potential costs associated with protecting cultural or archaeological resources.

The two liability categories evaluated in the SAAS are current and long term. Based on generally accepted accounting principles, when it is "sufficiently likely that an entity will not be able to avoid the future sacrifice of assets to settle the obligation" the liability must be recognized. The Sarbanes-Oxley Act of 2002 greatly increased the need for such liability reporting (Rogers, 2005). Therefore, the full commitment for BAFB's ERP and MMRP programs was tracked as a liability by the SAAS. Costs for these programs were obtained from the USAF, with the probabilistic AF$ simulated after the statistical cost variances of the programs were applied.

25.3.5 Equity and Income Statements

Overall, BAFB equity was calculated as the difference between assets and liability using the simulated AF$ totals from the Chart of Accounts. These totals were holistic and considered life-cycle cost over a 25-year period. The 2008 income statement was generated from the difference between the revenue and expense simulated AF$ totals from the chart of accounts. In total, the yearly income for 2008 was $50M AF$, contributing to a baseline equity of $4B AF$.

Using the SAAS, scenarios for energy projects were forecasted assuming the carbon values based on CCX. The following scenarios were evaluated:

- Baseline
- Gas-fired fuel cell
- Solar project
- Conservation of energy at 20 percent and a solar project.

Energy scenarios included operation of the gas-fired fuel cell, operation of a 25-million-kilowatt-per-year solar array, and a combined effort to achieve 20 percent reduction in energy and fuel usage along with operation of a solar array.

For all scenarios, the ROI and ROA were calculated and their impact on probabilistic equity increase quantified. Figure 25.2 illustrates the significant increase in ROI for a comprehensive renewable energy/conservation program.

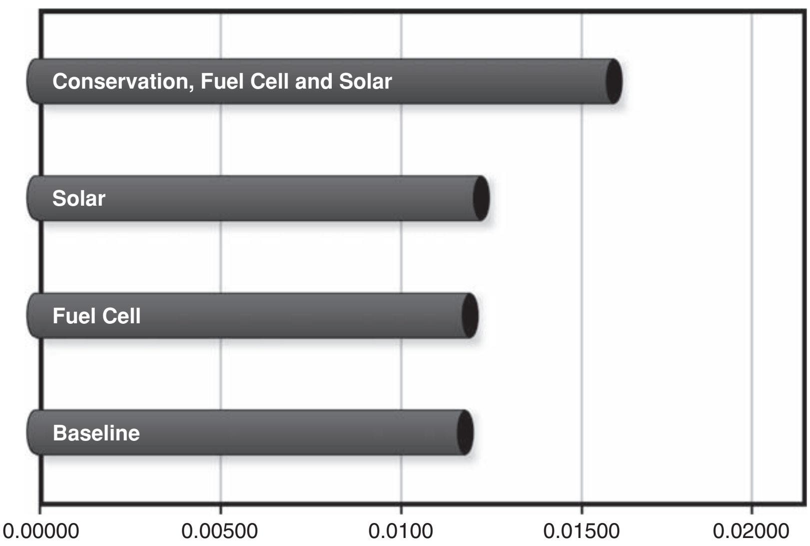

FIGURE 25.2

Return on investment for all scenarios.

25.4 CONCLUSION

To meet the federal mandates, the holistic, aggressive pursuit of renewable energy and conservation projects; physical plant reduction; and concerted asset management will be required as evident in ROI analysis. Several solution sets must be compared at a facility and portfolio level to understand the highest value path. Incorporation of carbon budget impacts into decision making is paramount when accurately accounting for the change in revenue and expense streams that will result from effectively designed projects. The SAAS provides a common platform, comparative analysis tool through which the ROA and ROI can be quantified and compared across installations, regions, and major commands.

Acknowledgments

The authors of this chapter would like to thank Air Combat Command, Air Force Center for Engineering and the Environment, U.S. Corps of Engineers, and the Air Staff for their support in the development of the tools discussed here.

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CHAPTER

Conclusion and Policy Recommendations

26

William L. Hall

In 1972, with the *The Limits to Growth* (Meadows, et al.), three scientists from the Massachusetts Institute of Technology (MIT) initiated a global conversation about resource use that exceeds the carrying capacity of the planet. Although the trajectory of resource availability versus resource use did not reach the catastrophic break points as quickly as predicted by Meadows and his colleagues, population growth, global warming, and land and forest loss have continued along the general scenarios laid out by them. In the 37 years since publication of *The Limits of Growth*, policy makers at all levels of government—from local municipalities to world organizations—have embraced the concept that societies cannot prosper indefinitely if they are mining their social and environmental capital.

The foundational message of this book is that the creation of sustainable human systems requires awareness of the built-in flaws in our thinking, an ability to think probabilistically about the consequences of our decisions, and a willingness to exert the emotional energy needed to build consensus. The hurdle lies in breaking the decision-making patterns that have been built into our species' DNA over millennia. These patterns may have been functional for our ancestors, whose ability to change their immediate environment, much less the global environment, was limited. But the decision-making patterns of the past become much more dangerous when a single individual on a Caterpillar tractor can clear 100 acres in a few days, and a family of four can dump as much waste into the commons as an entire medieval village.

The complexity of sustainable decision making adds to the difficulty of reaching consensus solutions. With the interconnection of so many disciplines and so many moving parts, the temptation is to retreat to tried and true heuristics. At one extreme is the true believer, the individual whose chosen set of beliefs is impervious to any challenge. He knows what he believes. His worldview or conceptual model is good by definition. The strong faith he has in his beliefs is its own justification of their righteousness. A true believer in the rightness, or righteousness, of a particular system, be it political, economic, religious, or social, has the conceptual models of how

DOI: 10.1016/B978-1-85617-797-9.00026-5

the world works tied down. Not only is any alteration of those models unacceptable, but it may actually be viewed as evil. When the world doesn't work the way it should for such a person, his task frequently becomes a search for whatever can serve to prop up his models.

At the other end of the spectrum is the rigorous analytical scientist who believes only what can be measured. For her, truth is that which is consistent with the data and not fatally contradicted by any relevant information. Unfortunately, the rigorous scientific model is an ineffective antidote to the true believer. It can only influence the individual who is willing to engage in the unflinching rigor needed to follow where the data actually leads.

Given the incredible levels of complexity in ecological systems, adherence to scientific rigor is not possible for the average decision maker. And for the scientist, it can lead to paralysis or retreat into a cycle of questions that plunge her into an ever deepening void of unanswerable uncertainties.

Into this void steps the engineer, the politician, the businessperson—or simply the charlatan—who has an answer to sell. Both ends of the spectrum are tempted to grasp at whatever is being sold if the seller is sufficiently confident and implies that any pain will be borne by the other, real culprits. The sale is helped even further if what is being sold is labeled "green," "sustainable," or "renewable" and it is packaged in pleasant earth tones.

Decision consequence analysis is not a simple, magic answer to the conundrum of sound sustainable decision making and policy formulation. Rather, it is a disciplined approach for identifying, acknowledging, and measuring uncertainty, and for creating the opportunity for feedback mechanisms to function. It offers a framework for capable decision makers at varying levels of technical competence in the relevant disciplines to collectively align measures of success with core objectives. When decision makers adopt this framework in developing, implementing, and evaluating policy, they can help to create and encourage sustainable systems that function as intended.

With the tools described herein, the authors hope to at least incrementally improve society's capacity to move toward sustainable interaction with the natural systems upon which it depends. These tools strengthen the alignment of values with reality. For values, when stripped of the veneer and vanity of rhetoric, are simply the scales on which we test the balance of our life's journey. They are our measures of success. And our measures of success will dictate the legacy we leave for those with no voice in our choices.

We are attracted to measures of success that have tangible weight and heft. The result is that we are too often troubled to action only when our world can be converted to cash and we are unable to sustain more than casual care for what lies beyond the fence lines of time and space. These fence lines block our horizons and leave us to make decisions and develop policies based on assumptions that are nearly always at least partially, and often outrageously, wrong. The creation of a sustainable relationship with our world for our children, grandchildren, and beyond requires expansion of our horizons beyond the mere measure of a life's span to the very edge of human imagination. We must analyze the holistic consequences of our actions to understand that economic, social, and ecologic systems are one and cannot thrive unless nurtured together.

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