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Series C: Environmental Security

Climate

Global Change and Local Adaptation

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Preface

Through altered weather patterns and a rise in sea level, climate change is expected to significantly alter coastal and inland environments for humans, infrastructure, and ecosystems. Coupled with uncertain predictions for sea level rise and storm frequency and intensity, potential land use changes and population increases present a significant planning challenge. Even though significant resources have been directed to predicting potential consequences of climate change, additional emphasis is required to develop rational approaches to guide decision making under uncertainty and methods to develop and compare the performance of alternative adaptive strategies within an overall adaptive management approach.

Regardless of current efforts to mitigate climate change, plans must be developed to adapt to the risks that climate change poses to humans, infrastructure, and ecosystems. The idea for this book was conceived at the NATO Advanced Research Workshop (ARW), "Climate Change: Global Change and Local Adaptation," held in June 2010 in Hella, Iceland. The workshop was attended by 60 scientists, engineers, and policymakers representing 14 different nations and multiple fields of expertise, reflecting the global and interdisciplinary nature of climate change research.

This book considers integrated environmental assessment and management as part of the nexus of climate change adaptation. Risk analysis has emerged as a useful approach to guide assessment, communication, and management of security risks. However, with respect to climate change, the complexity of the problem, the time and spatial scales of relevance, and the uncertainties associated with long-range predictions present critical challenges to current analytical approaches to inform risk management decisions. The objectives of the workshop involved discussion of an integrated, multicriteria, multi-hazard, risk-informed decision framework suitable to evaluate climate change adaptation strategies. The objectives were met by examining the following five issues:

- State of science regarding vulnerability and impacts at local and regional scales
- Role of risk analysis in managing the potential risks
- Applicability of adaptive management

- Strategies developing countries can use to manage the potential security risks
- Specific research needs to improve the value of risk analysis as applied to climate change

The organization of the book reflects major topic sessions and discussions during the workshop. Part I summarizes societal and political needs for climate change adaptation. The introduction by the President of Iceland, Olafur Ragnar Grimmson, highlights the important new national and international security challenges that may be posed by climate change. Steven Stockton, director of the U.S. Army Corps of Engineers (USACE) Civil Works Program, and Lynn Scarlett, former deputy secretary of the U.S. Department of the Interior, describe the environmental and engineering research priorities facing the USACE and similar agencies and engineering organizations worldwide, and also discuss the importance of stakeholder involvement to policymakers involved in setting regulatory and policy agendas that have the potential to affect local, national, and international communities.

Part II summarizes the state of the science in climate change adaptation. Uncertain predictions of sea level rise, storm frequency, and intensity have led to the investment of significant resources in accurately forecasting the potential consequences of climate change, but in a relatively very short time frame (certainly less than 5 years). Methods and tools of risk assessment, multicriteria decision analysis, adaptive management, sustainable development, and technology innovation are all presented and discussed in the context of tangible and practical applications to support management decisions.

As demonstrated by the remaining sections, workshop participants reached a consensus on three important areas of social and environmental concerns surrounding climate change adaptation: the process for changes in coastal regions, the process for changes in inland regions, and the potential challenges to security for national governments. Each section reviews achievements, identifies gaps in current knowledge, and suggests priorities for future research in topical areas. Each part begins with a group report summarizing consensus principles and initiatives from workshop discussions. The wide-ranging content of these sections reflects the participants' diverse views and regional concerns.

Part III discusses challenges in coastal regions. Coastal regions have a unique set of vulnerabilities, which contribute to current and future risks. Even though governance plays a critical role in enabling or disabling productive adaptation responses, individuals and communities also perform a fundamental role in the adaptation process. There is a need to engage people in progressive analysis and planning for expected and uncertain climate-induced events, as well as the adaptation process necessary to ensure that actions in response to climate change meet the objectives and preferences of stakeholders. The section highlights the application of powerful concepts and tools currently available to plan and manage adaptation at local and regional scales.

Part IV discusses the varied range of vulnerabilities facing inland regions, including potential changes to soil quality, water quantity and quality, ecosystem services, fire and other natural forces, and abrupt or inevitable changes in land use. In addition, inland regions are be pressured by climate impacts on coastal regions, as was the case with Baton Rouge, Louisiana, in the aftermath of the Hurricane Katrina disaster in 2005. Recommendations for an improved framework for climate adaptation with respect to inland regions are fundamentally more challenging to identify than coastal regions due to the wide variations in ecosystems and human population and our current gaps in science and technology. Human use of inland ecosystems must be sustainable. Planning also will need to address how communities should handle both rapid and gradual environmental changes, which could otherwise undermine long-term adaptation.

Maintaining national security by avoiding undue internal and external stresses that may disrupt the normal functioning of nations, states, enterprises, and citizens is one of the primary duties of any national government, as discussed in Part V. National security involves collaboration among various national and international agencies and organizations such as the military, civilian police services, emergency preparedness and responses services, and aid and humanitarian organizations. The safety and security of societies may be threatened in subtle and profound ways by climate change. Little doubt exists that the effects and impacts of climate change in different parts of the world will vary widely. In order to effectively contemplate likely futures and scenarios of climate-induced adaption, science and engineering knowledge and tools are needed.

Climate change is a global environmental threat. Simultaneous advances in different disciplines are necessary to advance climate change adaptation. This book reflects the ongoing efforts of scientific organizations, governments, professional societies, and international agencies to examine the nature of impending environmental and social changes and the likely course of human adaptation to those changes.

March 2011 Igor Linkov and Todd S. Bridges
(with input from NATO ARW participants)

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Chapter 1
Climate Change and New Security Challenges*

O.R. Grimsson

Ladies and Gentlemen

It is an honor and a privilege to address you on a subject which for the last 10 years has profoundly influenced my intellectual journey and official responsibilities.

The people of Iceland have witnessed the alarming melting rate of our glaciers, which have long been the largest in Europe. The pace of retreat is so striking that some mountains and valleys which have been covered by ice for centuries are now visible for the first time.

My country can thus be described as a theater of the climate change process. This is not only because of the glaciers but also due to our struggle with the largest desert in Europe. We are also aware of how the Gulf Stream encircles our island, joining with the water produced by the melting of the Arctic and so creating what can be described as the motor which drives the global conveyor belt of ocean currents, influencing the climate in Asia, Africa and the Americas.

Iceland can also serve as an inspiration, as an example of how to battle climate change through comprehensive transformation of the energy systems. In the early years of my life, over 80% of Iceland's energy needs were met by using coal and oil. Now 100% of our electricity is produced from clean energy sources, and over 75% of our total energy needs, including fuel for cars and shipping, are met by hydro or geothermal power. Within the lifetime of one generation, we have transformed Iceland from being predominantly a fossil-fuel user into a world leader as regards the production and consumption of clean energy.

The abundance of clean energy is the main reason why Iceland is now, notwithstanding the financial crisis, an attractive investment location for foreign companies. An ever-growing number of investors are willing to go anywhere if

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they can get permanent and secure access to clean energy, thus becoming well positioned when a global carbon tax, in one form or another, is introduced. This magnet nature of clean energy production is especially important for twenty-first century IT investments, for software and information-based companies. For this reason, an abundance of clean energy will give countries a strategic advantage in the twenty-first century global economy.

The people of Iceland have also been able to meet the setbacks caused by the collapse of our major banks and the global financial crisis partly because our energy economy was transformed some years ago to provide cheap clean electricity and space heating, making the economic hardships for families and homes less severe than in many other countries.

There are more than 100 countries in the world that could effectively use geothermal resources in this way, and we are now helping cities in China to replace coal plants with geothermal to provide urban heating, cooperating with Djibouti to formulate plans which could make it the first clean-energy country in Africa. We have also engaged in extensive discussions with the U.S. Administration, the Department of Energy, members of the U.S. Senate and the House of Representatives, governors and mayors, to map out the role which geothermal power could play in the transformation of the U.S. energy economy, contributing to the security of the country, limiting dependence on the import of fossil fuels, reducing the risks caused by fluctuating oil prices and providing opportunities for new infrastructures, supporting the cities and regions where the resources are located.

Thus, our small country is involved in many different types of international collaborative work in the energy field. To me, perhaps the most fascinating one is with Abu Dhabi.

I strongly believe that if we could do this, so can others. The fight against climate change is fundamentally about the future of energy.

Global warming could clearly be slowed down or even averted if the Icelandic model were followed on a global scale by utilizing the variety of clean energy resources available to every country.

The problem is, however, that time is short and the hurdles are enormous. Unfortunately, it seems wise to prepare our nations and the international community for dealing with the consequences of climate change.

In recent years we have gained increasing awareness of how our eco-world is in fact a single system, how developments in one particular area of the grand mechanism of our existence may have hitherto undreamt-of consequences in another. The most dramatic contemporary manifestation of this interdependence is the relationship we have come to understand between climate change and the destruction of the soil, and how this constitutes a vicious circle.

Land degradation, manifested in the loss of carbon from the terrestrial ecosystem, is one of the major contributors to the buildup of greenhouse gases in the atmosphere. As land loses its cover and vegetation retreats, its capacity to capture carbon is reduced, and this in turn accelerates climate change. Warmer years may result in droughts, affecting water resources and an endless number of eco-systems, often furthering the spread of dangerous diseases.

A formidable body of scientists estimates that we only have 10–15 years to transform our systems in ways which could prevent irreversible effects of climate change. Others argue we might have 20–30 years. In either case, it is a very short time. Even the ultimate optimist might find it difficult to believe that our national economies and our global system could be radically altered within such a short time-span.

I do, however, believe that it can be done. In this sense I am the ultimate optimist, yet I am also a realist, molded by decades of involvement in national and international politics and decision-making. I know that the pace of reform can be slow and frustrating. Even if you can lead the horse to the water, with strong and persistent goading, it is not easy to make him drink.

It therefore seems to me to be prudent to follow two simultaneous and parallel courses of action.

One involves the transformation of our energy systems, our life-styles, our societies and our economies, in order to minimize, and preferably prevent, climate change. Although this is a colossal task, it can be achieved, especially if we are guided by the same sort of vision and confidence as inspired the ending of the Cold War and brought mankind through the Great Depression and two World Wars into a new security framework.

The other course of action consists of preparing for the disastrous consequences of the global warming which is now already on the horizon, to engage in a comprehensive and profound dialogue on the new security challenges and to map out how global and regional institutions could tackle the tasks ahead.

The International Alert report has claimed to identify "46 countries at risk of violent conflict and a further 56 facing a high risk of instability as a result of climate change."

Environmental challenges can often translate into armed conflicts, as demonstrated by recent examples of how soil erosion becomes the root cause of humanitarian crises, vicious and tragic ethnic confrontations. Darfur is but one example. A score of countries in Africa, Asia and elsewhere, have seen the deterioration of the land and the enlargement of the deserts threaten to sow the seeds of severe conflicts in the years to come.

It is important to understand the complex ecological, economic and social interplay of land use, water resources, energy production and carbon emissions. Increased greenhouse gas emissions will bring higher temperatures and in consequence more wind; lack of water will erode the soils in densely populated areas which are highly dependent on traditional agriculture. Now the Caspian Sea and the Lake Chad, two huge water reservoirs, have more or less disappeared, leaving large regions open to dust and wind erosion.

At the same time, the accelerated melting of the Greenland and Antarctic ice caps, similar to what is happening to the glaciers of Iceland and the Himalayas, will make the ocean level rise considerably, washing away excellent farmland soil in Bangladesh, the Mekong Delta and various other parts of the world. With increased poverty, social unrest, even warfare, people have very little chance of using their farmlands in a sensible and far-sighted manner.

Many small island states are giving high priority to these security concerns. For them, the prospect of a rise in the sea level and destructive hurricanes poses a greater threat than any military scenarios have done up to now.

Similarly, continental states with long and low coasts are rapidly becoming aware of what could happen. This applies to prosperous and poor nations alike. Around a fifth of the planet's population lives in coastal areas which are threatened by rising sea levels. Hurricane Katrina and the fate of New Orleans was therefore a wake-up call, not just for the United States but also others.

Recently we have woken up to what is happening in the Himalayas, an area that is sometimes referred to as "the water-tower of Asia," containing reservoirs for over a billion people and providing the basis for both food and energy production.

The deterioration of the Himalayan glaciers and their water systems is a strong reason for India and China to monitor current and future climate change more closely than ever before; to become active partners in the search for solutions.

Thus, China and India could suffer the most immediate and disastrous consequences suffered by any country. Their leaders might argue, correctly, that it is grossly unfair that the two billion or more people living in those countries should be so severely affected when climate change is primarily caused by the economies of Europe and America.

Since for China and India the stakes are indeed higher than for most Western countries, it is, in my opinion not inconceivable that they could, in the next 10–20 years, achieve greater CO_2 reductions than either the U.S. or Europe. The common excuse, which is so often quoted, for non-action in the West—that China and India are not doing enough—might thus be reversed. By 2025, the two Asian giants could be calling on the U.S. to match their CO_2 reductions.

Although the prospect in the Himalayas is among the most alarming ones to be found, we must acknowledge that all nations, wherever they are in the world, will be disastrously affected by climate change. It is therefore necessary that every state become a constructive partner in an advanced global dialogue on the security implications of climate change, even if this dialogue is mostly of an exploratory nature in the early phases.

We need to move from the old ways of looking at national, regional and international security towards the unfamiliar yet urgent challenges that lie ahead. The international institutions which were established in the aftermath of the Second World War were based on traditional security analysis. It is now important to emphasize, that the multilateral system is at risk if the international community fails to address the threats associated with climate change.

It is therefore timely and wise to start examining these new security issues systematically. The following list of relevant areas alerts us to the complicated task involved, to the conflicts which the warming of the planet could create:

1. Widespread water crises caused by the drying up of lakes and rivers, by the spreading of deserts and melting of glaciers. Since many of the Earth's biggest rivers run through many countries, the drying up could cause nations to take

drastic and even military action to secure their own water supplies. Already, water systems in the Middle East are under intensive stress. Two thirds of the Arab world depends on water resources originating outside their borders, and Israel might lose 60% of its water supply this century. China with a fifth of mankind only has access to a small part of the global water reserves.

2. In all continents, the reduction of arable land will have a severe impact on food security and create an acute crisis for hundreds of millions of people. Historically, conflicts over water and land, the basis of agricultural production, have led to wars in Europe and elsewhere. Climate change would introduce gigantic dimensions into these traditional causes of military conflict.
3. Increased flooding and prolonged droughts would intensify these developments and make it extremely difficult to deal with them in a comprehensive and systematic way, especially in view of the fourth item on my list.
4. Migration between states, regions and even continents could reach a level hitherto unknown. The migrants would be climate refugees trying to escape droughts, hunger, water shortages and rising sea levels; looking for new and secure homes because theirs have been destroyed by storms or flooding. Almost two billion Asians live within 35 miles of the coastlines and a large proportion of them will lose their homes as a result of rising sea levels.
5. The urge to enter countries which fare better in an era of climate change could grow to such an extent that all the resources and capabilities of the more fortunate countries would be threatened to the same degree as if they were faced with a massive military invasion. Furthermore, deep-rooted ethnic and religious tensions could escalate and might lead to radicalization and conflicts that would prove almost impossible to control.
6. Fragile and weak states would be in danger of collapsing, and small island states could see all or most of their territories disappear. Thus, entire state structures could wither away, leaving the populations in a political no-man's land and entirely reliant on emergency aid from abroad. Similarly, communities within states, communities with special ethnic or historical characteristics, might see their land destroyed, causing great strains on the capacity of the respective national governments. The consequences could be some form of civil war or other prolonged conflicts.
7. Climate change will also have a dramatic impact on our energy systems, on our capacity to generate electricity and harness the power which is the basis of our economic prosperity. Rising sea levels could damage oil and gas reservoirs and make some inaccessible. We have only to call to mind the problems of the Middle East in recent decades and the importance of oil to realize what could be at stake.
8. The energy resources in the Arctic, amounting to a quarter of untapped global stocks, are also relevant with respect to the new security dimensions created by climate change. The placing of the Russian flag on the ocean bed by a submarine expedition was a sign that a new security era has dawned in the Arctic. Access to the region's energy resources could be a strategic advantage in the twenty-first century global economy.

9. The opening of new sea routes caused by the melting of the Arctic ice, both the Northern Sea Route and the Bering Sea Route, not only shortens the ocean trade routes from Asia to Europe and America in a revolutionary way but also requires systematic arrangements and formal agreements involving Russia, the United States, Canada and the Nordic countries. These sea routes could become as important for global trade in the twenty-first century as the Suez and Panama Canals were in their times—and those canals gave rise to serious tensions and military conflicts. It is clear that control over the new sea routes which climate change opens up in the Arctic will confer enormous power and wealth on those countries that find themselves in key geographical positions.
10. Humanitarian crises caused by extreme weather events will become more frequent and more dramatic, creating societal and cross-border stresses with the potential for multiple security implications. Many such crises occurring simultaneously would severely test the capacity of the existing international institutions. The global demand for relief action could put the Security Council and other UN bodies into a more challenging crisis than they have ever envisioned.

The 10 areas of new security concerns caused by climate change which I have here briefly outlined support the view that we must use the next few years to build consensus and agreements on necessary measures, otherwise the consequences of climate change could become more tragic than we ever imagined, even causing upheavals in the global institutional framework that was created after the Second World War.

We were able to contain the Cold War by a series of treaties which at first seemed unattainable. We witnessed the building of a new democratic and free Europe within a single decade, transforming global politics from deadly confrontation to a more interconnected world.

We were able to land a man on the moon and gain extensive knowledge of its landscape but have now to face the startling fact that we know less about the Earth's oceans than the lunar desert.

It is therefore of utmost importance to marshal our forces, both nationally and internationally, in order to prevent disastrous global warming since the consequences of failure could aggravate old tensions and trigger new ones all over the world, spilling over into violence, wars and military threats. Countries in Europe, Asia, Africa and both the Americas will be affected. No one will be immune from these threats to the permanent security of our nations.

Chapter 2
Climate Adaptation

Science and Collaborative Decision Making

L. Scarlett

Abstract Climate change adaptation is at the intersection of science, communities, and a decision-making context characterized by multiple spatial and temporal scales and high levels of uncertainty, complexity, and dynamism. Potential approaches to adaptation include shared governance, adaptive management, establishing improved system indicators and metrics, and assessing ecosystem services benefits. Addressing climate change also requires evaluating the role of scientists in the decision-making process.

2.1 Introduction

Climate change and its effects on people and places present a medley of potential effects—sea level rise, thawing permafrost, changes in precipitation patterns, increased frequency of high-intensity rainfall events, impacts on flora and fauna, and many other changes to the environment. These changes have been well documented [11].

At the Interior Department, I chaired the Climate Change Task Force. The Task Force examined how climate effects might unfold across 500 million acres of Interior-managed lands, affecting resources and infrastructure at 2,400 locations with 165,000 facilities. The Task Force explored both adaptation and mitigation options. Its deliberations were situated at the confluence of science, technology, communities, management, and policy.

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There's a passage in the children's book, *Alice in Wonderland*, by Lewis Carroll, in which the heroine Alice stands at a fork in the road.

Alice looks up to see the grinning Cheshire Cat. She asks the cat, "Would you tell me, please, which way ought I to go from here." The cat replies: "That depends a good deal on where you want to get to." For communities grappling with a changing climate and its effects, their response to the Cheshire Cat might be that they are striving for risk reduction and sustainability (however defined).

The challenge is, of course: How? Where? What? Who? When? From the vantage point of a policy maker, I offer a few thoughts on the intersection of science, communities and decision making. Through that lens, I'll highlight four features of the climate change tableau that complicate decision making and affect how we think about institutions, information, and actions. These features are not wholly unique to climate change. However, they are distinctive in their breadth, depth, pace, and scale at which they are manifested in the climate change context. These four features include:

- Multiple spatial and temporal scales of the climate change problem set
- High levels of uncertainty about those effects, particularly regionally and locally
- The interconnected complexity of the changes underway that result from multiple variables, non-linear interactions, a hyper-volume of interacting axes, and links among issues, across landscapes, between people and place, and even across time
- The highly dynamic context in which multifaceted climate change effects intersect with demographic, economic, and land use changes

2.2 Discussion

Consider the first feature of the climate change context—the multiple spatial and temporal scales of change. Many climate effects transcend the boundaries of political institutions. Sea level rise, for example, along the Gulf of Mexico, affects multiple communities, even multiple states. Climate effects transcend boundaries and span different time horizons. Some effects are significant and near-term, such as currently observed changes in sea-ice in the Arctic region. Others are long-term and iterative, as may occur in the responses of some wildlife to climate change.

What are the implications of this first feature for decision makers? Nations and their communities will need institutions and decision processes that facilitate coordination across jurisdictional boundaries and among public and private land managers. They will also need both horizontal and vertical interaction among multiple governing units. Such interaction is not new. Indeed, the governing framework in many nations involves some sharing of public decision making and a vertical distribution of governing roles and responsibilities.

But these forms of federalism and regional decision making may require a different character to respond effectively to the challenges of a changing climate. Social scientist Kirk Emerson describes "collaborative federalism," with joint decision making among multiple governing units [2]. The model she describes is one of "shared governance," not divided decision-making authorities and responsibilities in which governing functions and issues are segregated and parceled out among different levels and units of government.

The concept of shared or collaborative governance may be applicable at the regional scale among local, interacting jurisdictions that are striving to coordinate policy and action where responding to climate effects requires cross-jurisdictional action. But collaborative federalism presents challenges. As the Lincoln Institute (Cambridge, Massachusetts) has pointed out in its discussions of regionalism [8]: How might one convene and motivate a cross-jurisdictional polity?

Policy makers also face practical challenges associated with limits on their authorities to expend funds outside jurisdictional boundaries. Yet such expenditures may be important. Consider source water protection in which relevant lands may lie outside a city's, or even a nation's, boundaries. Or consider the need to sustain cool, instream water temperatures or augment instream flows along an entire watershed. Or consider beach replenishment along coasts, in which sediment deposition may be required outside a city's boundaries to secure the desired protections.

Two central challenges confront efforts to facilitate multi-jurisdictional governance. Fundamentally, policy makers face the challenge of how to achieve a decision scale "big enough to surround the problem, but small enough to tailor the solution" [8]. Second, policy makers face a challenge of how to share both goal-setting and financing across governing units and among the public and private sectors.

Within this context of shared governance, federal agencies may shift their roles from that of provider to facilitator—what Steve Stockton of the U.S. Army Corps of Engineers (USACE) refers to as the "Home Depot Model"—"you do it, we help."

Cross-boundary governance options include both structural and nonstructural tools. Structural tools include the creation of dedicated agencies, districts, and institutions. Nonstructural tools include service agreements, partnerships, joint programs, and other informal coordinating arrangements. Both may be relevant, depending on regional issues and circumstances. Cross-national political, cultural, social, and economic distinctions will shape and limit the possibilities of shared governance.

In the U.S., we see many emergent models of cross-jurisdictional collaboration. In southeastern Wisconsin, 28 municipalities with separate stormwater management authorities have joined in a public-private partnership to create a trust to coordinate stormwater management in an area encompassing six watersheds [9]. In the Tualatin Basin of Oregon, water managers combined four wastewater permits and one stormwater permit into a single cluster and partnered with the farmers in the county and the U.S. Department of Agriculture to plant trees within the watershed to reduce water temperatures [9]. Both partnerships are issue-specific. Very few U.S. examples present models of multipurpose, cross-jurisdictional government.

A second feature of climate effects complicates decision making: the high level of uncertainty regarding these effects, particularly at regional and local scales. This characteristic of climate change effects makes ongoing learning imperative and highlights the significance of adaptive management and what the National Academy of Sciences has referred to as a "deliberation with analysis" decision model [7].

Adaptive management in the context of resource management refers to a decision-making model in which:

1. Goals are set, a process that is fundamentally about values and invokes the importance of legitimacy, relevance, and feasibility as key filters.
2. Action options are developed and intentionally designed as experiments to evaluate scientific assumptions and action effectiveness.
3. Ongoing monitoring is undertaken.
4. Results are reviewed.
5. Adjustments to management practices are based on the monitored results and analysis.

In a review of adaptive management, the National Academy of Sciences in the U.S. reports that experience to date indicates limits to the applicability of adaptive management [7]. Specifically, this approach may be most feasible where four conditions are met. Adaptive management may be most effective when:

- Temporal and spatial scales are relatively small.
- Dimensions of uncertainty are bounded so that option experiments can yield clear results.
- Costs, benefits, and risks of experimentation are acceptable and course corrections are tolerated.
- Institutional support exists for flexibility and adjustments.

These features may not apply to many climate issues and contexts. Thus, some analysts suggest a "deliberation with analysis" model may be more relevant [7]. This model refers to decision processes that provide for:

1. An iterative formulation of a problem, which is not solely a technical matter
2. Identification of interests and values relevant to defining objectives and addressing the problem
3. Development of a shared understanding of risks
4. Crafting of options and possible responses using this shared knowledge

Recognizing the limitations of how adaptive management has been practiced, USACE is developing a model of "enhanced adaptive management" that situates adaptive management within a decision framework of goals set through collaboration and evaluated using scenario planning. This framework would overcome some of the limitations described by the National Academy in its critique of how and when adaptive management might be a useful management tool. Depending on the particular climate issue, different decision models may be appropriate.

The ubiquity of uncertainty underscores the need for flexibility, resilience, iteration, and adaptive responses in decision tools and action options. High uncertainty also underscores the central role of science and technical expertise in decision making about whether, when, and how to respond to the effects of a changing climate. But the centrality of science and technical expertise raises a conundrum of what some have referred to as the "technocracy versus democracy" quandary.

Climate change issues are highly technical and complex. But policies and adaptation decisions may significantly affect people and involve tradeoffs. These differential effects on people heighten the relevance of community collaboration and present a fundamental question. How is it possible to increase public involvement in decision making when the scientific and technical issues associated with some climate effects challenges are so complex? What are the roles of scientists and technical experts?

The role of science in decision making is fluid and varying. The relationship of scientists to decision making unfolds along a continuum of low engagement to high engagement. That continuum is described by Denise Lach and her colleagues as clustering into five potential roles for scientists [6]. At one end of the spectrum with minimal engagement is a reporting role in which scientists report research to decision makers. A slightly more active engagement includes reporting and interpretation of scientific information. Third is a role in which scientists report, interpret, and then integrate their scientific information and analysis into policy or management options. Beyond this integration, some scientists may actually advocate particular policy or management options. At the far end of the spectrum are circumstances in which scientists participate in making policy choices.

What is the appropriate role of scientists? How can relevant science inform policy and management decisions? The joint fact-finding model described and used by the U.S. Geological Survey and others holds some potential more strongly to link scientists, decision makers, and publics affected by policy decisions [5]. Under that model, articulated and practiced by former U.S. Geological Survey scientist Herman Karl and others, scientists, decision makers, and citizens collaborate in the scoping, conduct, and employment of technical and scientific studies to improve decision making.

Such collaborative settings may be especially significant in enhancing prospects that scientific and technical information will be incorporated into resource policies and management. Studies on knowledge use show importance of iterative dialogue and the importance of decision contexts and mechanisms (such as joint fact finding) that link researchers to users. Such iterative dialogue can also provide for adaptive research outputs, the two-way flow of information, and actual uses of knowledge.

The user context also can significantly affect whether and how scientific and technical information are used. In part, USACE's enhanced adaptive management model is designed to provide this context and these linkages. Substantial research indicates that mere reception of knowledge by users does not imply use. A lack of interaction between researchers and their intended audiences can present a significant problem that limits the relevance and perceived credibility of research that is intended to inform public policy decisions.

The context of uncertainty invokes other important questions about science and policy. How much certainty about a particular cause/effect sequence or about projected futures is enough? Scientists use the protocol of a 95% confidence level as the bar necessary to affirm scientific results in a research context. Policy makers use a different bar—for policy makers or managers, how much uncertainty is acceptable invokes the reply: “It all depends.” It depends on the legal or policy context that might dictate immediate action despite uncertainties [9].

Think of water management in the West. Water managers don’t know with certainty the timing, amounts, and storm frequencies that a changing climate might bring to the West. But managers may need to take steps to alter water management despite these uncertainties. Thus, the question of what level of certainty is sufficient to take management action is, in part, a policy decision.

Though much more might be said of the science-policy interface, a third feature of the climate change problem set—the interconnected complexity of climate change effects—also challenges decision makers. Consider a case in the Netherlands regarding sea level rise and river flows. In the Dutch “Room for the River” project, managers indicate that, on one hand, they need to plan for higher river flows through improved drainage [4]. On the other hand, sea level rise interferes with water drainage. Improved flood protection and water management, therefore, require considering both river flows and sea level. One issue cannot be addressed independently of the other.

This interconnectedness raises challenges of agency silos in which responsibilities for issues are divided. It also raises challenges for metrics: how might managers develop cross-issue indicators to measure outcomes on integrated basis?

Scientists and others in the Everglades and elsewhere have begun to develop “dashboard” indicators and winnow down a welter of indicators into accessible, smaller subsets. These efforts strengthen the science-management interface. But consider two challenges. Metrics are often calculated in terms of location-specific targets for, say, species populations. Are these the right metrics? Do location-specific population targets cause us to lose sight of the forest for the trees? Many metrics are focused on particulars rather than an integrated whole. Quantum physicist David Bohm once observed: “To fragment is to divide things up that are at a more fundamental level actually connected” [1].

To enhance ecosystem health, resource managers need a combination of system process indicators and population metrics. This challenge raises a corollary issue: resource management requires both “richness”—detailed knowledge of specific ecosystem components—and “reach”—a broad knowledge of interacting components and natural systems [3, 10]. In short, good resource management requires both specific and integrated information. Resource managers also need interpretation—what do indicators mean? I am reminded of a caution once offered by economist Thomas Sowell, who remarked: “Information everywhere but knowledge is rare.”

But let us now turn to the last feature of climate change effects: dynamism. Climate effects are highly dynamic, with the pace of change sometimes dramatic (as in current trends with Arctic sea-ice melting).

Like the characteristic of uncertainty, the highly dynamic nature of climate change effects implies the need for adaptation. It may also heighten the need for policy options centered on resilience or robustness. More specifically, resource managers need management options that provide functionality across a broad range of conditions.

Consider water management and flood protection. In the case of coastal protection, traditional flood and storm surge protection has relied on "gray" infrastructure such as dikes and levees. This infrastructure may perform well under certain conditions. Yet increasing the performance of this gray infrastructure to withstand more frequent and more intense storms may be exorbitantly expensive in many cases relative to solutions that supplement existing gray infrastructure with green infrastructure like beach nourishment, wetlands restoration, and sea marsh protections. The latter mix of options may provide greater functionality and more resilience across a broader range of conditions than traditional infrastructure. Moreover, such green infrastructure may provide habitat protection, enhanced water quality, and other co-benefits.

Or consider reservoirs, which, traditionally, have been built for the dual purposes of water storage and flood control. With an increased frequency of high-intensity rainfall events or prolonged droughts, revising reservoir operations to maximize water storage capacity in combination with restoring flood plains to serve the flood protection role may offer communities greater resilience than building ever-larger reservoirs that operate as dual-purpose systems. Comparing these options renders consideration of "Nature's Capital"—ecosystem benefits—especially relevant.

Calculation of such benefits should not be confused with ignoring what some refer to as the intrinsic value of nature. Ecosystem benefits assessment and the intrinsic value of nature are not dichotomous concepts.

Instead, the challenge resides in selection of methodologies associated with assessing intrinsic values. Because such values are not traded in a marketplace, assessing such values requires use of tools such as contingent valuation—exercises in assessing what people "would" pay to sustain natural places and ecosystems. Disagreements often arise regarding the selection and use of such tools.

Challenges also reside in determining the role of such ecosystem benefits valuations within an overall decision framework. Specifically, how much weight does one place on such valuations—or cost-benefit valuation in general—in resource management and infrastructure investment decisions?

2.3 Conclusion

The governance, information, and adaptation challenges presented by climate adaptation responses invoke no single set of policy and institutional answers. But risk reduction and sustainability will require a confluence of science, collaboration, and new forms of governances. These three dimensions of problem solving are important to enhance decision-making effectiveness, accountability, and legitimacy.

Twenty-first century governance, as the Lincoln Institute in Cambridge, Massachusetts, has pointed out, may reveal a new lexicon of collaboration, shared power, networks, consensus, and iteration. All these features, for policy makers, make decisions provisional, and they diffuse responsibilities. This sort of diffuse, provisional decision making is difficult to reconcile with traditional notions of accountability.

With this backdrop, I conclude by returning to an earlier issue—the broad relationship of science and decision making. The intersection of science and decision making presents difficult questions. Science is critical to understanding causes and effects, filling knowledge gaps, projecting future outcomes, modeling alternative options, and assessing restoration results. Many climate adaptation issues are sufficiently scientifically complex that science at the decision table may help pinpoint the possible and define the doable. Scientists may help decision makers and managers shape and evaluate options through iterative conversations. They may help decision makers define the "problem set" but this input requires strengthening the iterative processes by which information needs are articulated and information is generated, communicated, and used. But what information do decision makers need? Scientists ask: "how does the world work?" [9] Scientists' reputations are often built upon the dissection and discernment of complexities and new frontiers. They often provide "deep knowledge" and highly specialized knowledge. Policy makers and managers have a different set of tasks and knowledge needs. Policy makers ask: what values do we care about? What priorities should we set? What actions should we take to address those priorities? Fundamentally, these questions involve the "people factor."

At one level, the very nature of these questions invokes the importance of citizen engagement. Situation complexity requires complex decision-making processes of coordination, partnerships, and collaboration. But, in other respects, managers need simplicity. At an operational level, managers (and policy makers) need information that allows for nimble, sometimes quick action. They need a general sense of progress or signals of impending problems. They need easily accessible, readily comprehended information. Policy makers and managers need general benchmarks, easy-to-use models and decision support tools. Within a resource management context, this tension between the aims of the scientist and the needs of the manager sometimes eludes resolution.

As nations and communities ponder these issues, governing institutions, and the intersection of science and decision making, the words of Bertrand Russell offer a fitting caution:"Sometimes we need to hang a question mark on things long taken for granted."

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Chapter 3
U.S. Army Corps of Engineers' Collaborative Approach to Twenty-First Century Challenges Posed by Global Change

S.L. Stockton and K.D. White

Abstract It is now clear that global changes, including demographic shifts, changing land use/land cover, climate change, and changing social values and economic conditions, are part of a complex system that cannot effectively be dealt with by piecemeal or sequential problem-solving. These changes can interact and combine in unpredictable ways, resulting in potentially surprising or abrupt changes that threaten public health and safety, the performance of water resources infrastructure, and the functioning of ecosystems. The U.S. Army Corps of Engineers (USACE) sees these global changes that result in local impacts and responses as the major challenge of the twenty-first century. We also recognize that close collaboration, both nationally and internationally, is the most effective way to develop practical, nationally consistent, and cost-effective measures to reduce potential vulnerabilities resulting from global changes. This paper will discuss how USACE is leading the way to solve the challenges of the twenty-first century through our collaborative approach.

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3.1 Introduction

As the largest and oldest federal water resources management agency in the U.S., the U.S. Army Corps of Engineers (USACE) oversees and administers public water resources and associated infrastructure in every state, as well as several international river basins. For more than 230 years, the USACE has supplied engineering solutions to water resources needs, including navigation, flood and coastal storm damage reduction, protection and restoration of aquatic ecosystems, hydropower, water supply, recreation, regulatory, and disaster preparedness and response. Approximately 12 million acres of land and water resources are under the jurisdiction of the USACE as part of its Civil Works portfolio of more than1,600 water resources projects, programs, and systems. USACE also applies water resources management expertise to support military program operations worldwide that promote peace and stability.

The cross-jurisdictional and multiscale nature of USACE water resources management, combined with the wide variety of water users and their differing requirements, has resulted in management policies and procedures designed to respond to changing needs and balance competing needs. These policies and procedures improve the capacity of water managers to absorb additional disturbances without unduly impacting their basic functions.

In the past decade, it has become clear that global changes, including demographic shifts, changing land use/land cover, climate change, growing state capabilities, aging infrastructure, disappearing wetlands, and changing social values and economic conditions, represent a new set of challenges that USACE must be prepared to face. These changes are part of a complex system that is not completely understood. Global changes can vary nationally, regionally, and locally, and can confound each other and can combine in unpredictable ways to result in potentially surprising or abrupt changes that can pose a threat to public health and safety, the nation's water resources infrastructure, and natural ecosystems.

3.2 USACE Water Resources Management

3.2.1 Historical USACE Approach

Since 1802, USACE has been a leader in water resources management and the development and operation of water resources infrastructure based on the best available science and technology. Up through the late twentieth century, this included designing and engineering structures based on an "equilibrium paradigm," which assumed that natural processes (e.g., precipitation and runoff) tend toward a stable equilibrium condition. Land use, land cover, and other changes in the landscape could result in an altered equilibrium state, but this could be represented generally based on the characteristics of the equilibrium state. In the case of hydrology, where time series data provide the basis for water resources design, this meant that designers could assume stationarity of the data. In other words, the mean, variance, and autocorrelation of the time series could be assumed to be constant over time [37]. Therefore, observations of the past were thought to accurately represent the future [26] and could be used in engineering design.

3.2.1.1 Assumption of Stationarity

The assumption of stationarity allowed engineers to plan and design water resources projects against projected future conditions even where observed records were relatively short compared to the expected life of the project. This assumption allowed for substantial water resources development in a time when detailed analytical or dynamic representations of physical processes were not available and computational capabilities were limited. Though hydrologists and hydrologic engineers understood that stationarity can be an oversimplification [7], the use of conservative design standards based on stochastic or probabilistic analysis, plus a factor of safety, resulted in designs that, for the most part, were resilient to unexpected events.

3.2.1.2 Evolution of Problem-Solving Approach

During the twentieth century, not only did water resources engineers expand their knowledge of hydrology and hydraulics, they also developed standard methods for use in hydrology and hydraulic engineering [7, 18, 22]. Increased observations, record length, and advances in modeling and computing supported increasingly detailed analyses of the uncertainties and variability in time series data and projections of future conditions. Changing social values led to increased pressure to evaluate the costs and benefits of water resources projects and reduce costly conservatism in design. At the same time, improved understanding of hydrologic and hydraulic processes, combined with the need to perform reliability analyses of aging infrastructure, led to risk-based engineering design and assessment [6].

Risk-based approaches require accurate projections of future operating conditions and consequences associated with extreme or unexpected events. The more detailed analyses required by risk assessments highlighted the complex interaction of global changes in the watershed, including climate change, land use and land cover, and evolving ecosystem structure and function. Improved numerical and computational resources allowed engineering problems to be explored in greater depth. Problem-solving no longer required as many simplifying assumptions (e.g., heterogeneous vs. homogeneous material properties or rapidly varied vs. uniform flow). Methods progressed to allow variations and perturbations in initial and boundary conditions, resulting in alternate futures and allowing the assessments of the sensitivity or physical variables and calculated parameters. The need for capacity to evaluate water resources management issues through a systems approach became evident [15].

3.3 New Global Challenges to Water Resources Management

Just as our problem-solving approach adapted to changing knowledge and technologies, our approach to developing and implementing effective solutions for current and future water resource needs changed with increased understanding of the uncertainty of the future. As we look to the future, our twenty-first century challenges include aging infrastructure, decreased availability of funding, and increased demands on the nation's water resources caused by population expansion and changes in water demands, the need for environmental sustainability, and management of the impacts of climate change to water availability and quality.

The era of large, federal, single-purpose water resources projects is over, as is the USACE's role as the single decision maker and technical expert for water resources solutions. The water resources community recognizes the need for the broader, more collaborative, regional water resources planning to meet twenty-first century needs described below.

3.3.1 Twenty-First Century Challenges

As we look to the future, we see that water conflicts will persist, especially where there are already conflicts between water supply storage and flood storage, between water supply and environmental flows, and among other competing water sectors. Responsibility for water resources management will continue to be shared, requiring improved intergovernmental cooperation and improved water resources. Challenges we see ahead include:

- Demographic Shifts: the U.S. population is expected to reach almost 400 million by 2050[1] [8]. The population is expected to become increasingly urbanized and concentrated in coastal communities at risk from severe weather and lack of fresh water.
- Global Challenge: The world population is expected to increase from 6.1 billion in 2000 to 8.9 billion in 2050 [33], though growth rates will decrease. Global population growth leads to increased demand for scarce water. Currently, nearly 900 million people are without access to clean water, and more than 2.5 billion people are without adequate sanitation [36], and these numbers are likely to increase as population grows. Our role will be to promote regional stability, using integrated water resources management as a means to promote transboundary cooperation.
- Aging Infrastructure: The American Society of Civil Engineers gave an overall grade of "D" to U.S. infrastructure in 2009 [1]. Estimates to bring our infrastructure

[1] Estimate from the "middle series;" the high series estimate is ~520 million, while the low series estimate is ~280 million.

to an adequate level range up to $2.2 trillion. Many USACE facilities, including over half our navigation locks, are already beyond their 50-year "design life." They will require extensive maintenance and rehabilitation. Failure of this critical water resources infrastructure poses risk to human health and safety, the economy, and the environment.

- Globalization: Foreign trade is an increasing share of U.S. economy, with exports reaching 12.7% of U.S. GDP in 2008 [19]. Though economic conditions in 2009 were difficult for exports as for other areas of the U.S. economy, the U.S. ITA expected that economic recovery would depend in part on exports [21]. The inability of ports and inland waterways to handle this increased demand could limit economic growth.
- Water-Energy-Food Nexus: The nexus between water, energy, and food is highlighted in the increasing role of sustainability in policy making. Factors include increased development of hydropower as clean source; the role of waterways in the transport of coal, petroleum, and natural gas: and estimates of the volumes of water needed for new sources.
- Environmental Values: Pressure from increased development—including rapidly growing demands for food, fresh water, timber, fiber, and fuel—has substantially affected the natural environment [23]. Supporting sustainable water resources management will require a cultural shift including lifestyle changes as well as technical innovation.
- Climate Change: Climate change exacerbates existing global changes. Already observed changes in snowmelt, floods, and droughts are likely to progress over time, potentially affecting all aspects of water resource management.
- Declining Biodiversity: Our knowledge of ecological structure and function has evolved over time. The importance of biodiversity is being recognized at a time when global changes are resulting in decreased biodiversity. Freshwater species in particular are facing loss of habitat and increasing rates of extinction [24]. Important questions related to biodiversity, global changes, and habitat, and their relationship to water resources management, remain to be addressed.

USACE sees these global changes that result in sometimes unexpected regional and local impacts and responses as the major challenge of the twenty-first century. We recognize that close collaboration, both nationally and internationally, is the most effective way to develop sound, nationally consistent, and cost-effective measures to reduce potential vulnerabilities resulting from global changes.

3.3.2 Recognizing Nonstationarity

Global change requires water resources managers to move from the equilibrium—or stationary—paradigm to one of constant evolution that recognizes the dynamic nature of physical and socioeconomic processes. Successful water resources management requires us to anticipate surprise and unexpected events, both natural and socioeconomic, and to respond effectively in a timely manner. Water resource managers now and in the future must make assumptions and decisions about supply, demand, weather, climate, and operational constraints that differ in spatial and temporal scale and uncertainty. We must provide our stakeholders and partners with data and information that allows them to make risk-informed decisions as well. Over time, uncertainty may decrease as we increase our knowledge of climate change, its impacts, and the effects of adaptation and mitigation options (including unintended consequences). The use of rigorous adaptive management, where decisions are made sequentially over time, allows adjustments to be made as more information is known. The use of longer planning horizons, combined with updated economic analyses, will support sustainable solutions in the face of changing climate that meet the needs of the present without compromising the ability of future generations to meet their own needs.

3.3.3 New Approaches

3.3.3.1 Systems Approach

USACE is fortunate that a systems approach has been a fundamental organizational perspective beginning with the establishment of the USACE Civil Works Divisions and Districts along the hydrologic boundaries of major river basins in 1802 [35] (Fig. 3.1). The systems approach was affirmed when the Mississippi River Commission (MRC) was formed following catastrophic flooding in 1874 to develop plans for the areas along the Mississippi River, prevent flooding, and promote navigation. The watershed approach was also specifically noted in Section 3 of the Flood Control Act of 1917: "All examinations and surveys of projects relating to flood control shall include a comprehensive study of the watershed or watersheds…" as well as later documents from the 1930s to the 1980s.

Following the events of Hurricane Katrina in 2005, the USACE undertook an analysis of the performance of the Southeast Louisiana Hurricane Protection System plus other information internal and external to the USACE. In response to the lessons learned, USACE renewed its efforts to implement a comprehensive systems approach in a manner that that shifts the decision-making focus from individual, isolated projects to an interdependent system and from local or immediate solutions to regional or long-term solutions [36]. This approach incorporates anticipatory and adaptive management to effectively manage our aging infrastructure in an environmentally sustainable manner with explicit risk management.

The comprehensive systems approach of the USACE to meet twenty-first century challenges is aligned with the National Research Council [27] definition of a systems approach:

> … the essential function of a systems approach is to provide an organized framework that supports a balanced evaluation of all relevant issues (e.g., hydrologic, geomorphic, ecologic, social, economic) at appropriate scales of space and time.

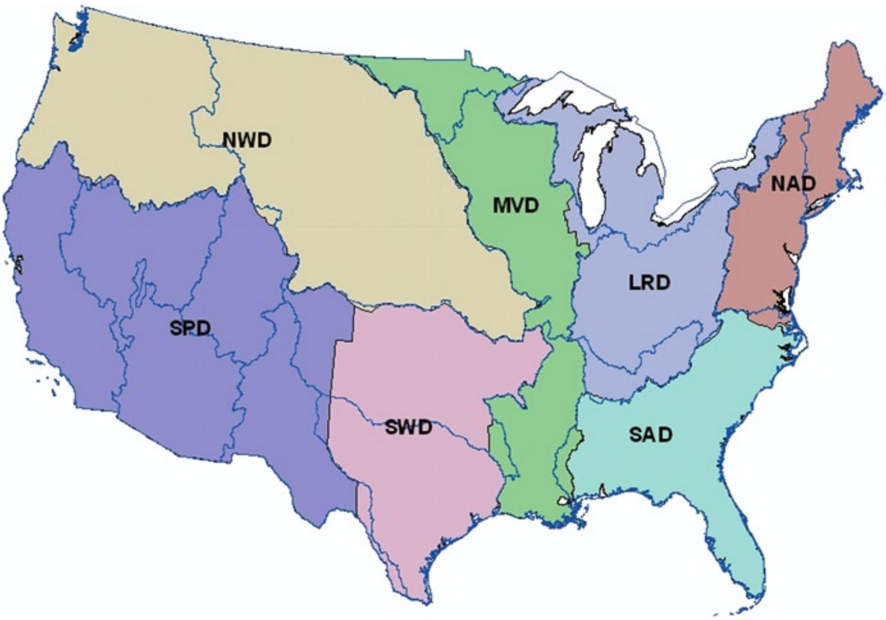

Fig. 3.1 USACE division boundaries in the continental U.S. are aligned with major river basins (Divisions shown in *colors* with three-letter designations, with USGS HUC-2 boundaries defined by *blue lines*)

For the USACE, this comprehensive approach entails the evaluation of projects and systems on larger geographic scales with a multiobjective perspective. USACE also recognizes the need to build multidisciplinary teams with other federal agencies, state and local partners, and the public to identify challenges and develop solutions that meet the widest spectrum of needs.

3.3.3.2 Decisions and Decision Scales

Water resources management agency decision making occurs at varying spatial scales from local to national, including international river basins, and on temporal scales varying from sub-hourly to multidecadal. Because water managers are largely concerned with resource management within surface and groundwater hydrologic boundaries, decision scales range from local to watershed to regional and can cross political, legal, and regulatory boundaries. Decision scales can vary from very general (e.g., feasibility study) to very detailed (e.g., engineering design or reoperations). The decision scale may be a function of the consequences of the decision. Decisions are subject to constraints including quality, budget, knowledge, staffing, and schedule.

Decisions about how to enhance the resilience of water resources management infrastructure requires reliable information about the variability and uncertainty of probable global change effects at the decision scale. A large portfolio of possible approaches to produce and apply global change information for water resource issues has been developed, often addressing each change component in isolation. Each of these introduces uncertainties or deficiencies, some of which are large or only partly characterized and poorly quantified. The choice of pathways among the portfolio of options and the level of effort these entail depend on the decision scale.

This is particularly true with respect to climate change. For example, the spatial and temporal scales available from most climate model projections may be too coarse to be usefully mapped to the scales of climate change adaptation decisions. There is a lack of guidance on how to determine the appropriate level of complexity in the analysis of climate information with regard to a particular decision and its likely consequences. For these reasons, USACE is working with other federal agencies charged with water resource planning and operating missions to address whether and how to develop guidelines and principles for producing climate change information they will use to support their variously scaled decisions on adaptation measures.

Water managers are also constantly adjusting to changing needs arising from shifts in population, development, land cover, industry, ecosystems, and social values, among other changes. The cross-jurisdictional and multiscale nature of water resources management, combined with the wide variety of water users and their differing requirements, has resulted in management frameworks designed to respond to changing needs and balance competing needs [29]. These frameworks improve the capacity of water managers to absorb additional disturbances without unduly impacting their basic functions.

3.3.3.3 Global and National Assessments

Water managers typically rely on information observed at global to local scales. Global and national scale information provides a context for long-term climate, geomorphological, and socioeconomic changes impacting water supply and demand. Global assessments of change available to guide water resources management decision-making include large multinational studies such as the Millennium Ecosystem Assessment [23, 24], and the Intergovernmental Panel on Climate Change.[2] National climate change assessments for the U.S. have been prepared by the Climate Change Science Program, now the U.S. Global Change Research Program.[3] These assessments include regional and sectoral assessments (agriculture, water, health, forests, and coastal areas and marine resources) as well as synthesis documents.

Other U.S. national assessments target specific areas of interest to water resources management, such as the U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program[4] or the Natural Resources Conservation Service

[2] See http://www.ipcc.ch/.

[3] See http://www.usgcrp.gov/usgcrp/default.php.

[4] See http://water.usgs.gov/nawqa/.

(NRCS) Conservation Effects Assessment Project (CEAP).[5] The importance of changes in land use and land cover in water resources management is addressed by several national assessments. A major assessment undertaken as a collaborative activity is the Multi-Resolution Land Characteristics Consortium (MRLC),[6] consisting of representatives of federal agencies: USGS, NRCS, Environmental Protection Agency (EPA), National Oceanic and Atmospheric Administration (NOAA), U.S. Forest Service (USFS), National Atmospheric and Space Administration (NASA), Bureau of Land Management (BLM), National Park Service (NPS), U.S. Fish and Wildlife Service (USFWS), and the Office of Surface Mining (OSM). MLRC provides four different land cover databases, including land cover, coastal change analyses, a dataset of habitat maps combined with wildlife models, and vegetation and wildland fuel maps. Example agency programs include the USGS Land Cover Institute[7] and the NASA Land-Cover and Land-Use Change (LCLUC) Program.[8]

3.3.3.4 Understanding Regional and Local Responses

The Millennium Ecosystem Assessment [23] demonstrated how changes in direct and indirect drivers at the global level can result in impacts to ecosystem, ecosystem services, and human well-being at the local and regional scale. But local and regional changes can also result in global impacts (Fig. 3.2). The cross-scale interactions that occur at varying speeds and spatial scales are increasingly coupled [17] and more complex. Though we may develop solutions for local problems at local scales, we must also explore the potential impacts of these solutions at larger scales of space and time. The complexity of global changes means that we can no longer apply piecemeal or sequential problem-solving, but must use methods suited to "wicked problems" [4, 12, 25, 32] that are "systemic, emergent, and participatory" [20]. The increased success of participatory problem-solving for complex systems is a foundation of the USACE collaborative approach.

3.4 Collaboration Is Key

Water resources managers in the U.S. are facing increased challenges due to climate change because it affects fundamental drivers of the hydrological cycle. Changes to important components of the hydrologic cycle—including precipitation, evaporation,

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[5] See http://www.nrcs.usda.gov/technical/nri/ceap/index.html.

[6] See http://www.epa.gov/mrlc/.

[7] See http://landcover.usgs.gov/.

[8] See http://lcluc.umd.edu/.

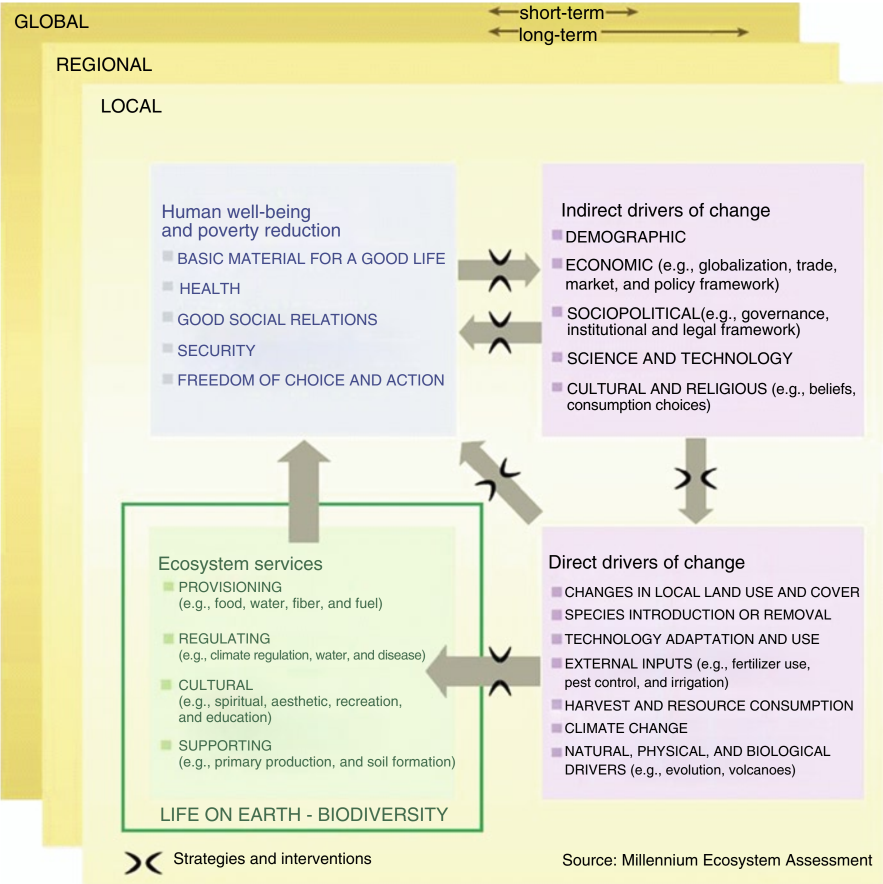

Fig. 3.2 Drivers of change (*indirect, top right*) and direct (*bottom right*) can result in changes to ecosystems and their services (*bottom left*) and human well-being (*top left*). The interactions between the drivers and resultant changes can occur at more than one scale and can cross scales [22]

condensation, and wind—can have profound impacts to the way we manage water resources now and in the future. Four examples of collaboration are presented below.

3.4.1 Water Management Collaboration: A Source of Resilience

Water resources management agencies have a special incentive to collaborate on water data, science, engineering, and operations: strong collaboration around water quantity and quality can result in a more secure and stable environment [35], whereas loose collaboration or competition over water can result in conflict and instability [30].

This collaboration is especially important given historical evidence that water and water resources management systems have been used as both offensive and defensive weapons in conflicts throughout the world [13, 14].

However, increased conflict over water due to twenty-first century challenges is not inevitable. The same skills used to handle twentieth century challenges of changing land use, demographics, and climate provide a reservoir of institutional knowledge and experience that can help to de-escalate conflict [15, 29, 39]. Water resources managers are uniquely positioned to develop and implement adaptively managed solutions to achieve positive outcomes [9, 35] through managing risks proactively rather reacting to prevailing crises and conflicts as climate changes. The USACE has actively engaged its fellow water resources management agencies in facing the challenges of the twenty-first century. Four examples are provided here that demonstrate our commitment to collaboration.

3.4.2 Building Strong Collaborative Relationships

The goal of the "Building Strong Collaborative Relationships for a Sustainable Water Resources Future Initiative," begun in 2008, is to identify and leverage opportunities for collaborative efforts and to create a joint national dialogue for water priorities between states, tribes and the federal resource agencies.[9] The initiative began by collecting and analyzing state water plans. They also brought together a variety of stakeholders to discuss critical water resources needs and potential response strategies. This initiative allows USACE to develop a comprehensive picture of water resources planning throughout the U.S. that identifies:

- Areas of water resource planning and management where states and regional entities feel their priority water needs are not being met.
- Regions or sectors where more integrated or comprehensive water resources planning and management within and across states is possible and advantageous.
- Topics for which the federal government might provide enhanced support to states and regions, especially for more integrated water resources planning and management.
- Opportunities for partnerships among states, regional entities, federal agencies, and NGOs to more effectively address comprehensive and integrated statewide and regional water resource and planning needs.

Three regional workshops were held in 2009, culminating in a national workshop in Washington DC in August 2009 and a report in 2010 [34]. Workshop participants included state and local representatives, interstate river basin commissions, federal agencies, nongovernmental organizations, and others involved in water resources

[9] See http://www.building-collaboration-for-water.org/.

management. The desired outcome of the workshops was to develop the strong partnerships necessary to begin working together on smart water resources investments based on a collective determination of needs and challenges. The initiative is designed to:

1. Develop more connected and complementary water management solutions across all levels of government.
2. Focus efforts on high-priority state and regional needs.
3. Reduce duplication of effort across government agencies.

These collaborative relationships and networks are being put into practice immediately in a wide range of USACE activities, a few of which are described below. In all cases, the richness of the collaborations has improved the outcomes for both USACE and its collaborators.

3.4.3 Water Management Agency Collaboration

In 2007, the four major federal agencies in the U.S. that manage water resources and water resources data and information collaborated to review climate change impacts to water resources and to lay out a path forward for how these agencies and others could collaboratively deal with climate variability and change. These four agencies, two termed "operating agencies" (USACE and the Bureau of Reclamation (Reclamation)) and two termed "science agencies" (USGS and NOAA) formed an unprecedented water management agency collaboration. The result of their work was a report published as USGS Circular 1331 "Climate Change and Water Resources Management: A Federal Perspective" in February 2009 [2].

This collaborative effort provides a foundation on which consistent future agency policies, methods, and processes will be based. Although geared toward the U.S., the findings of this report are applicable to other nations as they address climate change impacts to water resources. The key findings of Brekke et al. [2] related to climate change impacts to water resources are summarized as follows:

1. The best available scientific evidence based on observations from long-term (hydrometeorological) monitoring networks indicates that climate change is occurring, although the effects differ regionally.
2. Climate change could affect all sectors of water resources management, since it may require changed design and operational assumptions about resource supplies, system demands or performance requirements, and operational constraints. The assumption of temporal stationarity in hydroclimatic variables should be evaluated along with all other assumptions.
3. Climate change is but one of many challenges facing water resource managers. A holistic approach to water resources management includes all significant drivers of change.

3.4.4 Climate Change and Water Working Group

Given the pressing needs facing water resources managers due to already observed climate change impacts, the agencies involved in Circular 1331 decided a longer-term working relationship would improve collaboration. In 2008, they formed a group called the Climate Change and Water Working Group (CCAWWG) to work with the water management community to understand their needs with respect to climate change. Demonstrating alignment with the "Building Strong Collaborative Relationships for a Sustainable Water Resources Future Initiative," CCAWWG is actively fostering collaborative federal and nonfederal scientific efforts required to address these needs in a way that capitalizes on interdisciplinary expertise, shares information, and avoids duplication.

In 2009, the operating agencies of CCAWWG developed a two-phase plan to identify research priorities and opportunities for collaborative work within an integrated water resources management agency and science agency framework. In the first phase, they prepared an assessment of required capabilities, current capabilities, and gaps associated with incorporating climate change information into longer-term water resources planning. The report, *Addressing Climate Change in Long-Term Water Resources Planning and Management: User Needs for Improving Tools and Information*, was published jointly by USACE and Reclamation in January 2011 [3]. In response, the science agencies are developing a corresponding report containing a strategy for meeting these user needs.

USACE and Reclamation are currently preparing a CCAWWG draft report document, *Use of Weather and Climate Forecasts in Federal Water Resources Management: Current Capabilities, Required Capabilities, and Gaps*. This report is the second phase of the process, with the objective to identify capabilities and gaps as they relate to water management decisions with lookaheads of days to multiple years. The intended audience is federal and non federal partners and stakeholders that play a role in the daily delivery and multiyear scheduling of water in the U.S.

In January 2010, USACE hosted an expert workshop on *Nonstationarity, Hydrologic Frequency Analysis, and Water Management* in Boulder, CO [30]. This CCAWWG workshop was planned to address critical needs identified in USGS Circular 1331 about how and when to perform nonstationary hydrological analyses. Attendees were national and international experts on climate change hydrology. Discussions during the workshop addressed whether assumptions of stationarity are valid; use of different statistical models in nonstationarity conditions; trend analyses; how to use the output from global climate models (GCM); and how to treat uncertainty in planning, design, and operations. This workshop will result in a special issue of the *Journal of the American Water Resources Association*, and provide a basis for future policy development.

In 2010, CCAWWG added additional agency partners: Federal Emergency Management Agency (FEMA), EPA, Federal Highway Administration (FHWA), and Fish and Wildlife Service (FSW). The group conducted a second workshop on high-priority needs in November 2010, called, *Assessing a Portfolio of Approaches* *for Producing Climate Change Information to Support Adaptation Decisions* [5]. This workshop helped characterize the strengths, limitations, variability, and uncertainties of approaches for using climate change information to inform water resources adaptation planning and operations. This was undertaken in response to the need to develop a set of common tools for use in climate adaptation. This workshop will result in a special journal issue as well as other reports.

3.4.5 Participation on National Working Groups

The President's Council on Environmental Quality (CEQ) convened five interagency working groups in September 2009 to assist in developing a national strategy for climate change adaptation required under Section 16 of Executive Order 13514 [11]. The five working groups were: Adaptation Science Inputs for Policy, Water Resources, Agency Adaptation Processes, Insurance, and International Resilience Efforts. USACE has actively participated in these interagency workgroups, representing the missions and needs of water resources managers.

The CEQ [10] proposed a flexible Adaptation Process Framework to help agencies identify climate-based vulnerabilities, reduce those vulnerabilities through adaptive actions, and build greater resilience to climate change throughout agency missions and operations. The proposed framework has three components: (1) a set of principles to guide agency adaptation and resilience activities, (2) a six-step approach to climate change adaptation and resilience, and (3) a proposed set of government-wide enabling investments to support the effective implementation of the framework.

USACE is among four agencies currently testing the flexible adaptation framework. Pilot agencies will evaluate the implementation and utility of the flexible framework and document the outcomes and results of the pilot projects used to test the framework. The USACE is also participating in interagency teams developing a strategy for government-wide investments in basic common tools and processes to support climate change adaptation. The common tools will encompass processes, methods, and technologies that support climate adaptation. The outcome of the various CEQ working groups will be to develop a National Adaptation Strategy. Thus, USACE's collaborative approach to the pilot process should help to achieve a process that assists water resources managers as they develop strategies to meet future climate changes.

3.5 Summary

The global challenges facing water resources managers in the twenty-first century are immense. At the same time, resources are constrained. Water resources managers must work together to meet these challenges in a way that in a way that capitalizes on interdisciplinary expertise, shares information, and avoids duplication. USACE has evolved over time to meet water resources challenges posed by global changes. In doing so, we have embarked on a series of collaborative initiatives, with a wide variety of partners and stakeholders, to develop twenty-first century solutions to twenty-first century challenges. Examples of this collaboration include our *Building Strong Collaborative Relationships for a Sustainable Water Resources Future* initiative to achieve regionally tailored water management adaptation strategies; the interagency report USGS Circular 1331 Climate *Change and Water Resources Management: A Federal Perspective*; the Climate Change and Water Working Group; workshops addressing high-priority water resources management needs; and participation on national working groups with other agencies and the CEQ to develop and test methods and policies supporting the national climate change adaptation strategy.

We are putting into action our commitment to meet the global challenges of the twenty-first century through meaningful collaboration.

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Part II
Climate Change Adaptation as a Risk-Based Decision Problem

Chapter 4
Model Relevance

Frameworks for Exploring the Complexity-Sensitivity-Uncertainty Trilemma

S. Muller, R. Muñoz-Carpena, and G. Kiker

Abstract Ever more complex models play an important role in environmental assessment and adaptation to climate change. Model complexity is fundamental to the ability of environmental models to address questions, as well being a crucial determinant of uncertainty in model results. However, while increasing model complexity is introduced to answer new questions or reduce the uncertainty of the model outputs by considering refined process, often increased model complexity can have unexpected (and often unexplored) consequences on the overall model sensitivity and uncertainty. Thus modelers face a difficult trilemma relating model complexity, sensitivity, and uncertainty that can ultimately compromise the relevance of the model for a particular problem. We propose a methodological framework based on global sensitivity and uncertainty analysis to objectively and systematically explore this trilemma. An application is presented where a spatially distributed biogeochemical model to describe phosphorous dynamics in the Everglades (USA) is built and evaluated at different complexity levels. By increasing complexity, key model outputs were found to lose direct sensitivity to specific input factors and gain sensitivity to interaction effects between inputs. The relationship between complexity and uncertainty was found to be less predictable. Output uncertainty was generally found to reduce with increased complexity for summative outputs affected by the overall model (i.e., phosphorus surface water concentration), but reverse relationships were found for other outputs. The conceptual and methodological framework proved insightful and useful for characterizing the interplay between complexity, sensitivity, and uncertainty, and is proposed as an indispensable component in the model development and evaluation process.

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4.1 Complexity, Uncertainty, and Sensitivity: A Modeling Trilemma

> That is what we meant by science. That both question and answer are tied up with uncertainty, and that they are painful. But that there is no way around them. And that you hide nothing; instead, everything is brought out into the open [16].

A recent summary of the NATO Advanced Research Workshop on Global Climate Change and Local Adaptation [28] identifies models providing an integrated environmental assessment and management as a central component of the nexus of climate change adaptation. The study also concludes that additional emphasis is urgently needed on rational approaches to guide decision making through uncertainties surrounding climate change. This is because as is the case with all models [21, 39], those predicting climate change itself or models simulating the response of natural systems to this change (or to our proposed plans to address this change) produce unavoidable uncertainty around the predicted responses. However, in spite of the difficulties that the consideration of modeling uncertainty represent for the decision process, this consideration should not be avoided or the value and science behind the models will be undermined [5].

These two issues; i.e., the need for models that can answer the pertinent questions and the need for models that do so with sufficient certainty, are the key indicators of a model's *relevance*. For instance, a model may answer a question but its usefulness might be limited if the uncertainty surrounding the answer is large. Conversely, a model may be able to address many questions with acceptable accuracy, but if it cannot address the particular question of interest then it is not relevant. Model relevance is inextricably linked with model complexity. Zadeh [54] expressed this relationship in his *principle of incompatibility* for humanistic systems or similarly highly complex systems. According to this author:

> …stated informally, the essence of this principle is that as the complexity of a system increases, our ability to make precise and yet significant statements about its behavior diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristics.

Although model complexity has advanced greatly in recent years, yet there has been little work to rigorously characterize the threshold of relevance in integrated and complex models. Formally assessing the relevance of the model in the face of increasing complexity would be valuable because there is growing unease among developers and users of complex models about the cumulative effects of various sources of uncertainty on model outputs [11, 30, 31, 34]. In particular, this issue has prompted doubt over whether the considerable effort going into further elaborating complex models will in fact yield the expected payback [1].

More complex models include more state-variables, processes and feedbacks, and therefore have fewer simplifying assumptions. Model complexity, in turn, has direct implications for uncertainty [15], as shown in Fig. 4.1a.

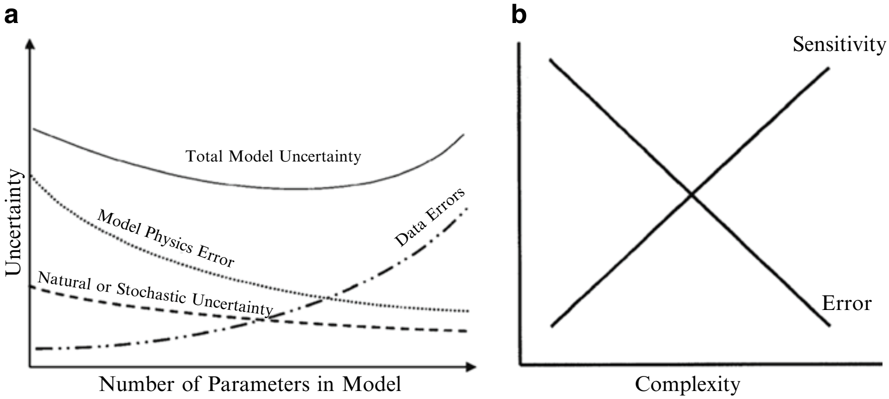

Fig. 4.1 (**a**) Trends in model uncertainty versus complexity [15]; (**b**) Trends in model sensitivity and error versus complexity [49]

Increased complexity can translate into less structural uncertainty (model physics error in Fig. 4.1a) and natural stochasticity (from spatial and temporal discretization). However, each additional process in a model requires additional model input factors, each of which is subject to uncertainty because of its intrinsic variability or data sampling errors. As complexity is increased and input factors accumulate, so too do the input uncertainties, which propagated onto the model outputs. Eventually a critical point is reached beyond which any additional complexity to reduce structural uncertainty is undermined by the accumulated input uncertainty—the threshold described by Zadeh [54].

In addition to input and structural uncertainty, overparameterization is another important source of uncertainty that is related to complexity. This issue can lead to problems of non-identifiability and non-uniqueness, which can fundamentally undermine trust in the validity of a given model [4]. Though difficult to quantify, the potential for overparameterization can be studied in terms of the sensitivity of an output to input factors [6, 49]. Though a general relationship relating complexity and sensitivity has been suggested (Fig. 4.1b) by Snowling and Kramer [49], this is another area that has not been widely studied [27].

Uncertainty analysis is the formal process of propagating input uncertainties through the model and onto the outputs. Sensitivity analysis determines what portion of the output uncertainty is attributable to the uncertainty in a given input factor, or to the interactions between input factors. Global sensitivity methods (those in which the complete parametric space of all the model input factors is sampled concurrently) should be used when evaluating complex models. However, the use of local sensitivity methods (derivative-based over a limited range and one factor at a time) remains pervasive [42]. Global sensitivity analyses offer additional benefits for managing uncertainty by helping to identify not only the important input factors for a given model output, but also their interactions. This information can be used to direct resources toward those input factors that would offer the best returns on resource investment. Conversely, unimportant input factors may indicate ways in which a model is unnecessarily complex, and therefore how it could be simplified. In addition, some cutting-edge methods of global sensitivity analysis have the benefit of employing Monte Carlo simulations, so results can be used for both uncertainty and sensitivity analysis [44]. This is an important efficiency since both global sensitivity and uncertainty analyses are generally computationally demanding, but work best when applied in tandem [44].

All modelers, but especially environmental modelers who often use complex models in increasingly integrated systems, face a difficult task. Relevant models must be available for environmental assessment of climate change, but in general we do not yet have a thorough understanding of how increasing complexity affects the behavior of models, particularly with respect to uncertainty. Rational and useful guidance is therefore needed to inform how model complexity is selected and managed. We propose that model relevance can be approached as a trilemma among model complexity, uncertainty, and sensitivity, and that this represents a useful conceptual framework within which to study the matter. Further, we propose a methodological framework of combined global sensitivity and uncertainty analysis as an efficient and effective means to explore and implement the relevance trilemma.

To demonstrate the utility of this approach, we present results obtained during the development of a complex, spatially distributed but user-definable numerical model of wetland biogeochemistry, including solute transport and reactions, developed for the Everglades wetlands of south Florida [17, 18]. The flexibility provided to the user to define the description of the wetland biogeochemistry offered the opportunity to explore, using global sensitivity and uncertainty analysis in a systematic and step-wise fashion, the effect of incrementally increasing the complexity of the conceptual biogeochemical model.

4.2 Challenges of Integrated Modeling for Evaluation of Climate Change Impact Scenarios

Throughout the history of environmental modeling there has been a natural tendency propelling the emergence of ever more complex models. There are many reasons: our knowledge has grown and we use models to synthesize this; we have a natural inclination to push our technological and intellectual boundaries; advances in processing speeds and programming languages have fueled this urge; and both the study and the globalization of environmental concerns have exposed more complex problems that legitimately require more complex tools to tackle. Meanwhile, efforts to facilitate simplification of models have also been growing [20, 24, 38, 41]. However models of large and growing complexity are here to stay.

Integrated modeling exemplifies today this tendency toward greater complexity, and represents an important modeling frontier. Integrated models link independent

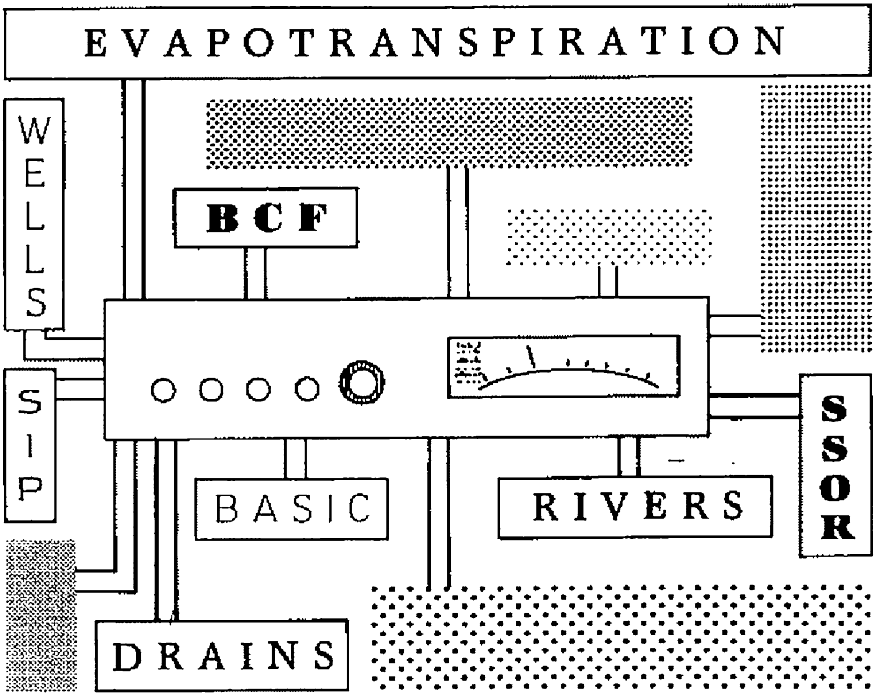

Fig. 4.2 Cover illustration from the original MODFLOW report [32] depicting the analogy of modules to a component stereo system

models (environmental, social, economic, and risk management) together, such that the output of one becomes the input for another, in an effort to take the holistic approach to the next level. This methodology is already being adopted as the best practice for future modeling in support of environmental assessment and management [12]. While technologically admirable, integrated models represent a new challenge to the formal assessment of model relevance because we know that model complexity will only reduce uncertainty to a point and, as explained, will likely increase it past this point [15, 23, 55].

The integrated modeling paradigm; i.e., the integration of *modules* within a particular model, was adopted relatively early in the history of modeling to promote the reusability and applicability of existing models. Models became more versatile by permitting modules to be turned on or off depending on the needs of the application. An excellent example of the modular approach, and its success, is the now ubiquitous MODFLOW [33], a groundwater flow model in which different aspects of groundwater simulation are handled by modules that may be turned on or off. At the time of its development this approach was compared with the idea of a "component stereo system," as shown in the original model schematic used for the report's cover illustration (Fig. 4.2).

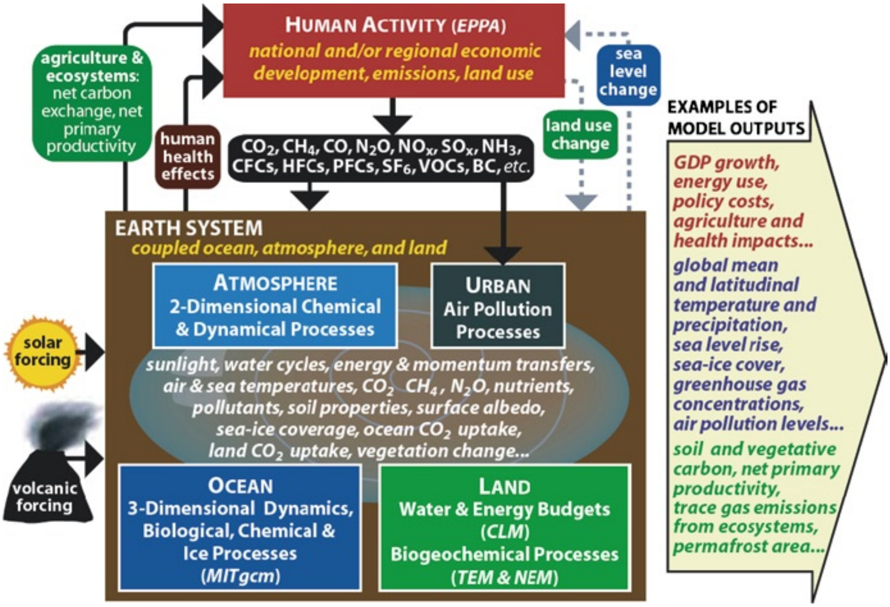

Fig. 4.3 Schematic of the MIT Integrated Global System Model Version 2 [50]

A modern example in the context of climate change assessment is the Integrated Global System Model (IGSM) Version 2 [50], which is composed of several linked models (Fig. 4.3), including the Emissions Prediction and Policy Analysis model; an atmospheric dynamics, physics, and chemistry model; an ocean model; the Terrestrial Ecosystem Model; a Natural Emissions Model; and the Community Land Model.

While MODFLOW is considered a complex model of groundwater hydrology, IGSM2 is a self-described earth system model "of intermediate complexity" [50]. A widely used definition of model complexity is a tally of the number of input factors (representing the underlying processes). By this metric, the IGSM2 is by far the more complex, yet it is not considered as such from within its particular community. The implications of this are that notions of model complexity remain unclear and subjective, and change meaning in the context of a particular application. In fact, the MODFLOW system of modules, intended to simulate the integrated processes controlling groundwater, is functionally analogous to the integrated models of IGSM2. However, one is immediately struck by an obvious difference between Figs. 4.2 and 4.3—the MODFLOW picture looks much less complicated. What's more, in the IGMF case, many of the specified components actually represent full models in their own right [51], themselves each comprised of modules not unlike MODFLOW's. The actual leap in model complexity—i.e., due to the much larger temporal and spatial scales of the integrated model—is even more dramatic than the visual comparison of model structures indicate. In cognizance of this, significant work to assess

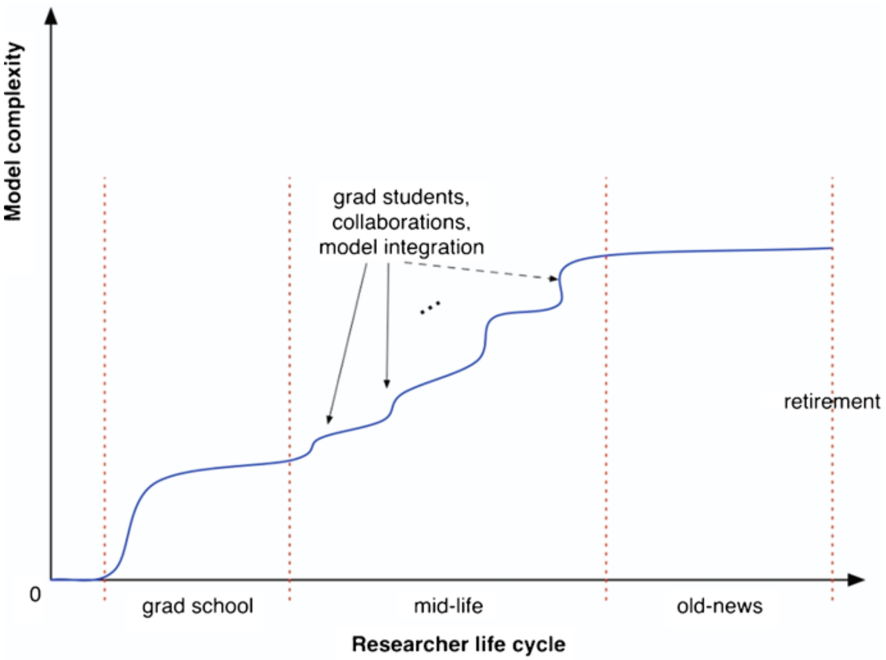

Fig. 4.4 Model complexity and the researcher's life cycle

and address uncertainty in the IGMF has been conducted [13, 50, 52]. However, this work generally focuses on evaluating the uncertainty of the end model, without consideration of alternative model complexities or their effect on model relevance.

We continue to rapidly increase the complexity of our models driven by external factors like the developer's life cycle (Fig. 4.4), without always acknowledging, rarely studying, and not yet fully understanding the profound implications complexity has for the uncertainty associated with their results.

Below we propose a methodological framework that serves to formally evaluate the effect of model integration and the relevance of the resulting model to the intended application.

4.3 A Methodological Framework for Assessing Effects of Model Complexity: A Case Study in the Everglades, FL

A case study for the analysis of the effects of increasing model complexity was carried out as part of a comprehensive testing process during the development of a numerical water quality model, the Transport and Reactions Simulation Engine (TaRSE), developed to simulate the biogeochemistry and transport of phosphorus in the Everglades wetlands of south Florida [17, 18].

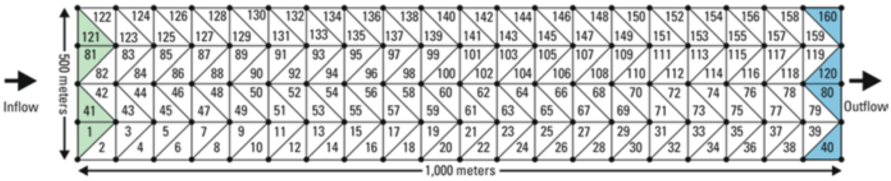

Fig. 4.5 Model domain used for testing of the transport and reactions simulation engine [18]

4.3.1 Model Description: TaRSE

TaRSE is composed of two modules; one that simulates the advective and dispersive transport of solutes [17], and one that simulates the transfer and transformation of phosphorus between biogeochemical components [18]. The term "Simulation Engine" refers to the generic nature of the reactions module, which was designed to be user-definable (by means of XML input files) such that the user specifies the state variables of the model and the equations relating them. State-variables that are transported with flow are termed "mobile", and those that are not are termed "stabile." TaRSE employs a triangular mesh to discretize the spatial domain for transport calculations [17] but the reactions module is independent of mesh geometry. Hydrodynamic variables such as depths and velocities can be specified as constant values by the user, as was the case in this work, or must be provided by a linked hydrologic model if variable hydrodynamic conditions are desired.

In addition to the necessary quality control provided by sensitivity and uncertainty analyses, the intention of this work was to study potential effects resulting from TaRSE's flexible design (i.e., user-defined complexity).

4.3.2 Model Application

In order to isolate the effects of complexity, an artificial domain was created in which the sources of variability extrinsic to complexity could be controlled and excluded.

A 1,000×200-m generic flow domain (Fig. 4.5) was created and discretized into 160 equal rectangular triangles (cells). Flow was set from left to right so that the inflow boundary consisted of cells 1, 41, 81, and 122, and the outflow boundary consisted of cells 40, 80, 120, and 160. A no-flow boundary was applied to the top and bottom (longer) edges of the domain. To exclude the effects of transient flow, steady-state velocity was established, and the effects of heterogeneities were managed by assuming spatially homogeneous conditions. A constant velocity of 500 m/day was established to approximate Everglades flow conditions [25] with a unit average water depth. Simulations were run for 30 days with a 3-h time-step.

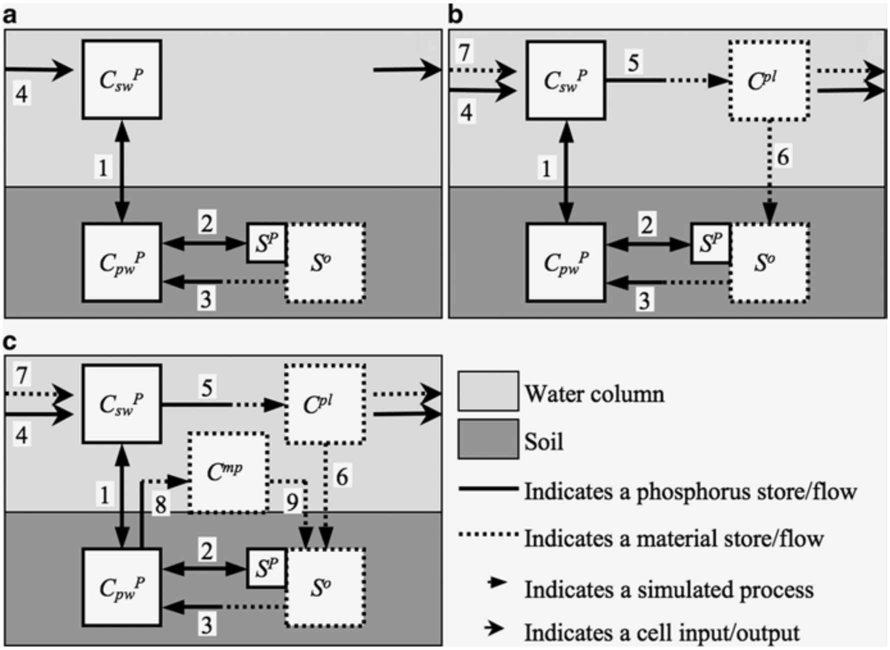

Fig. 4.6 Levels of modeling complexity studied to represent phosphorus dynamics in wetlands. Levels include (**a**) Level 1: interactions between SRP in the water column and SRP in the subsurface; (**b**) Level 2: Level 1 with the addition of plankton growth and settling; (**c**) Level 3: Level 2 with the addition of macrophyte growth and senescence. Notation and details on processes included in each Level are given in Table 4.1

4.3.3 Levels of Complexity

Three models of increasing complexity were created (Fig. 4.6a–c) by progressively adding complexity in an organized and step-wise fashion, as recommended in Chwif et al. [9]. One additional state-variable was introduced for each new complexity level. The processes required to integrate the new state-variables into the existing conceptual model were mathematically consistent formulations of biotic growth and loss, and required four additional input factors to characterize.

The simplest case (Level 1) contained no biotic components (Fig. 4.6a) and eight input factors were tested. The intermediate-complexity case (Level 2) contained surface-water biota in the form of phytoplankton (Fig. 4.6b) and 12 input factors were tested. The most complex case (Level 3) contained additional macrophytes rooted in the soil (Fig. 4.6c) and 16 input factors were tested. Table 4.1 lists the state-variables and processes that appeared in each complexity level, including the boundary conditions for the mobile state-variables (always quantified in g/m^3) of soluble reactive phosphorus (SRP) in the surface-water ($C_{sw}{}^{P}$) and plankton biomass (C_{pl}). Initial conditions for the stabile state-variables (always quantified in g/m^2) of SRP in the porewater, adsorbed phosphorus, macrophyte biomass, and organic soil

Table 4.1 Processes and variables used in defining three TaRSE models of increasing complexity

Process	Levels	Key, Fig. 4.6	Affected variables	Process equation
Diffusion	1, 2, 3	1	Surface-water SRP concentration (mobile), C_{sw}^{P} (g/m^3) Soil porewater SRP concentration (stabile), C_{pw}^{P} (g/m^2)	$\frac{dC_{sw}^{P}}{dt} = \frac{k_{df}}{Z_w Z_{df}}\left(C_{pw}^{P} - C_{sw}^{P}\right)$
Sorption-desorption	1, 2, 3	2	Soil porewater SRP concentration (stabile), C_{pw}^{P} (g/m^2) Soil adsorbed P mass (stabile), S^P (g/m^2)	$\frac{dS^P}{dt} = \frac{\rho_b k_d}{\theta}\frac{dC_{pw}^{P}}{dt}$
Oxidation of organic soil	1, 2, 3	3	Soil porewater SRP concentration (stabile), C_{pw}^{P} (g/m^2) Organic soil mass (stabile), S^o (g/m^2)	$\frac{dS^o}{dt} = -k_{ox}S^o$
Inflow/outflow of surface-water SRP	1, 2, 3	4	Surface-water SRP concentration (mobile), C_{sw}^{P} (g/m^3)	BC: C_{sw}^{P}=0.05 g/m^3
Uptake of SRP through plankton growth	2, 3	5	Surface-water SRP concentration (mobile), C_{sw}^{P} (g/m^3) Plankton biomass concentration (mobile), C^{pl} (g/m^3)	$\frac{dC^{pl}}{dt} = -k_g^{pl}C^{pl}\left(\frac{C_{sw}^{P}}{C_{sw}^{P} + k_{1/2}^{pl}}\right)$
Settling of plankton	2, 3	6	Plankton biomass concentration (mobile), C^{pl} (g/m^3) Organic soil mass (stabile), S^o (g/m^2)	$\frac{dC_{sw}^{pl}}{dt} = -k_{st}^{pl}C^{pl}$
Inflow/outflow of plankton	2, 3	7	Plankton biomass concentration (mobile), C^{pl} (g/m^3)	BC: C^{pl}=0.043 g/m^3
Uptake of porewater SRP through macrophyte growth	3	8	Soil porewater SRP concentration (stabile), C_{pw}^{P} (g/m^2) Macrophyte biomass (stabile), C^{mp} (g/m^2)	$\frac{dC^{mp}}{dt} = -k_g^{mp}C^{mp}\left(\frac{C_{pw}^{P}}{C_{pw}^{P} + Z_{as}\theta k_{1/2}^{mp}}\right)$
Senescence and deposition of macrophytes	3	9	Macrophyte biomass (stabile), C^{mp} (g/m^2) Organic soil mass (stabile), S^o (g/m^2)	$\frac{dC^{mp}}{dt} = -k_{sn}C^{mp}$

mass, were 0.05, 0.027, 500, and 30,000 g/m^2, respectively. Boundary and initial conditions were selected to represent reasonable Everglades conditions. Full descriptions and derivations of the model equations and their numerical implementations can be found in Jawitz et al. [18].

4.3.4 Model Parameterization

The analysis of TaRSE was intentionally performed without prior calibration in order to avoid limiting the potential range of physical conditions (input factor values) the model would be tested over, and through which the effects of new complexity would be expressed. Testing of models across a wide range of possible scenarios is a necessary step in the development process prior to evaluation of model performance for a particular application [43]. Before conducting the global sensitivity and uncertainty analyses it was necessary to specify the range and distribution for each input factor, from which values were statistically sampled using Simlab.

The field-scale ambient variability of many inputs has been reported to be adequately modeled with log-normal or Gaussian distributions [14, 19, 26, 29]. The (beta) β-distribution can be used as an acceptable approximation when there is a lack of data to estimate the mean and standard deviation for such probability distribution functions (PDFs) [53]. When only the range and a base (effective) value are known, a simple triangular distribution can be used [22].

The input factors used in the analysis of TaRSE (Table 4.2) were assigned ranges and probability distributions based on an extensive literature review found in Jawitz et al. [18]. The goal of this work was a general model investigation, and not a specific study of its application to a particular site. Consequently, input factor ranges that captured all physically realistic values for the target region were specified. This broad approach encompasses data from a wide range of physical and ecological conditions, and values were derived from relevant literature rather than calculated directly from sets of data. Consequently, the more general β-distribution was used for all biogeochemical input factors. Longitudinal and transverse dispersivity are related to aspects of the physical system that are contingent on site selection rather than natural variation, such as vegetation density, domain dimensions, and velocity. Their probability was therefore considered to be random, and accordingly allocated a uniform distribution.

Outputs were defined for each of the model's state-variables at each complexity level, and are described in Table 4.3.

In the context of this work to investigate the role of complexity, only those outputs that appear in all three complexity levels permit comparison and are presented. Outputs were defined to integrate spatial effects in stabile variables and temporal effects in mobile variables. For outputs of mobile quantities, averages across the outflow domain (cells 40, 80, 120, and 160) were calculated at the end of the simulation period. For stabile quantities, outputs were expressed as the difference between the initial and final value of averages across the entire domain.

Table 4.2 Input factors and distributions tested for using the global sensitivity and uncertainty analysis framework

Input factor definition	Symbol (alternate name in Fig. 4.7)	Key, Fig. 4.6	Distribution	Units	Input present in L1	L2	L3
Coefficient of diffusion	k_{df} (k_df)	1	β (7×10^{-10}, 4×10^{-9})	m^2/s	x	x	x
Coefficient of adsorption	k_d (k_d)	2	β (8×10^{-6}, 11×10^{-6})	m^3/g	x	x	x
Soil porosity	θ (soil_porosity)	2	β (0.7, 0.98)	–	x	x	x
Soil bulk density	ρ_b (bulk_density)	2	β (0.05, 0.5)	–	x	x	x
Soil oxidation rate	k_{ox} (k_ox)	3	β (0.0001, 0.0015)	1/day	x	x	x
P mass fraction in organic soil	X_{so}^{P} (chi_org_soil)	3	β (0.0006, 0.0025)	–	x	x	x
Longitudinal dispersivity	λ_l (long_disp)	4	U (70, 270)	m	x	x	x
Transverse dispersivity	λ_t (trans_disp)	4	U (70, 270)	m	x	x	x
Plankton growth rate	k_g^{pl} (k_pl_growth)	5	β (0.2, 2.5)	1/day		x	x
Plankton half saturation constant	$k_{1/2}^{pl}$ (k_pl_halfsat)	5	β (0.005, 0.08)	g/m^3		x	x
Plankton settling rate	k_{st}^{pl} (k_pl_settle)	6	β (2.3×10^{-7}, 5.8×10^{-6})	m/s		x	x
P mass fraction in plankton	X_{pl}^{P} (chi_pl)	6	β (0.0008, 0.015)	–		x	x
Macrophyte growth rate	k_g^{mp} (chi_mp)	8	β (.004, 0.17)	1/day			x
Macrophyte half saturation constant	$k_{1/2}^{mp}$ (k_mp_halfsat)	8	β (0.001, 0.01)	g/m^3			x
Macrophyte senescence rate	k_{sn}^{mp} (k_senesce)	9	β (0.001, 0.05)	1/day			x
P mass fraction in macrophytes	X_{mp}^{P} (chi_mp)	9	β (0.0002, 0.005)	–			x

Table 4.3 Definition of outputs and boundary/initial conditions used for the global sensitivity and uncertainty analyses

Output definition	Description	Nomenclature	Initial/Boundary conditions	Output present in		
				L1	L2	L3
Surface water SRP outflow (mobile)	Average of surface water SRP for outlet cells (boundary cells 40, 80, 120, and 160 in Fig. 4.16) at the final time step	C_{sw}^{P} (g/m^3)	0.05 (IC & inflow BC)	x	x	x
Soil porewater SRP variation (stabile)	Difference in averages porewater SRP concentration across the domain (all cells) between initial and final time step	C_{pw}^{P} (g/m^2)	0.071 (IC)	x	x	x
Organic soil accretion (stabile)	Difference in average organic soil mass across the domain (all cells) between initial and final time step	S^{o} (g/m^2)	30,000 (IC)	x	x	x
Soil adsorbed P variation (stabile)	Difference in average adsorbed P mass across the domain (all cells) between initial and final time step	S^{P} (g/m^2)	0.027 (IC)	x	x	x
Plankton biomass outflow (mobile)	Average plankton biomass concentration for outlet cells (boundary cells 40, 80, 120, and 160 in Fig. 4.16) at the final time step	C^{pl} (g/m^3)	0.043 (IC & inflow BC)		x	x
Macrophyte biomass accumulation (stabile)	Difference in averages of macrophyte biomass across the domain (all cells) between initial and final time step	C^{mp} (g/m^2)	500 (IC)			x

Except for structure, all model conditions were consistent across complexity levels, including fixed input factor ranges and distributions; invariant scale, initial, and boundary conditions; and steady hydrodynamics. Any change observed in the uncertainty and sensitivity was therefore attributable to the effects of changes in model complexity.

4.3.5 Global Sensitivity and Uncertainty Methods

Two state-of-the-art methods of global sensitivity analysis were applied: the qualitative method of Morris [35] and the quantitative, variance-based extended Fourier Amplitude Sensitivity Test (FAST) [42]. The latter method employs Monte Carlo simulations and results can therefore be used for uncertainty analysis as well. A brief summary of each method is given below (further details are summarized in Muñoz-Carpena et al. [37] and a thorough treatment of the methods is provided in Saltelli et al. [44]).

The Morris method, extended by Campolongo and Saltelli [8], applies a frugal sampling technique to efficiently explore the full parametric space of the model input factors. A one-at-a-time approach is used such that one input factor is varied while all other input factors are held constant. The change observed in an output, called the "elementary effect," can therefore be attributed to a particular input factor. This approach is analogous to the widely used derivative-based local sensitivity analysis methods, but is globalized by calculating multiple elementary effects after resampling the other input factor values in the model. In this way, the parametric space of the model is comprehensively sampled, and the magnitudes of the elementary effects are averaged to produce a qualitative global sensitivity statistic, μ^*. The magnitude of μ^* indicates the relative importance of each input factor with respect to the model output of interest [7]. The standard deviation of the elementary effects, σ, can be used as a statistic indicating the extent of interactions between inputs. High variability indicates that parametric context (the values of the other input factors) influences the elementary effects produced by varying a given input factor. This indicates that interactions between input factors can contribute to increasing or decreasing the sensitivity, or that output sensitivity to the input factor is non-linear. For each output of interest, pairs of (μ^*_i, σ_i) for each input factor can be plotted in a Cartesian plane to indicate the relative importance (μ^*_i) of each output (distance from the origin on the X-axis), and the prevalence of interaction effects (σ_i) between input factors (distance from the origin on the Y-axis).

The frugal sampling technique used in this approach makes it suitable for assessing the *relative* importance of input factors, sacrificing quantification in lieu of dramatically reduced computational demands. The Morris method is also useful for screening out unimportant input factors before conducting the much more computationally intensive Monte Carlo simulations required for quantitative analysis using the extended FAST method [18, 45].

The variance-based extended FAST method provides a *quantitative* measure of the direct sensitivity (S_i) of a model output to each input factor (i). It does so by calculating the fraction of the total output variance attributable to a single input factor. In addition to the calculation of first-order indices, the extended FAST method [42] calculates the sum of the first- and all higher-order indices for a given input factor (i), called the total sensitivity (S_{Ti}) index (Eq. 4.1),

$$S_{Ti} = S_i + S_{ij} + S_{ijk} + \ldots + S_{i-n} \tag{4.1}$$

where S_i is the first-order (direct) sensitivity, S_{ij} is the second-order indirect sensitivity due to interactions between input factors i and j, S_{ijk} the third-order effects to due to interactions between i and k via j, and so forth to the final varied input factor, n.

Based on Eq. 4.1, total interaction effects can then be determined by calculating $S_{Ti} - S_i$. It is interesting to note that μ* of the Morris [34] method is a close estimate of total sensitivity (S_{Ti}) [7]. Since the extended FAST method applies a randomized sampling procedure, it provides an extensive set of outputs that can then be used for the global uncertainty analysis of the model. Thus, PDFs, cumulative probability distribution functions (CDFs), and percentile statistics can be derived for each output of interest with no further simulations required.

4.3.6 Analysis Procedure

In general, the methodological framework followed six main steps (Fig. 4.7): (1) PDFs were constructed for uncertain input factors; (2) input sets were generated by sampling the multivariate input distribution according to either the Morris or FAST method; (3) model simulations were executed for each input set; (4) global sensitivity analysis was performed according to the Morris method and then (5) the extended FAST method; and (6) uncertainty was assessed based on the outputs from the extended FAST simulations by constructing PDFs and statistics of calculated uncertainty.

The software Simlab [45] (available at: http://simlab.jrc.ec.europa.eu/) was used for multivariate sampling of the input factors and post-processing of the model outputs. Sample sets were created for all the input factors in each of the complexity levels tested (see subsequent section and Fig. 4.6) and for both methods, resulting in a total of six sets of analyses. The number of model runs was selected based on the number of input factors in each complexity level according to Saltelli et al. [44]. A total of 1,170 simulations were conducted for the Morris method and 45,046 simulations for the extended FAST method.

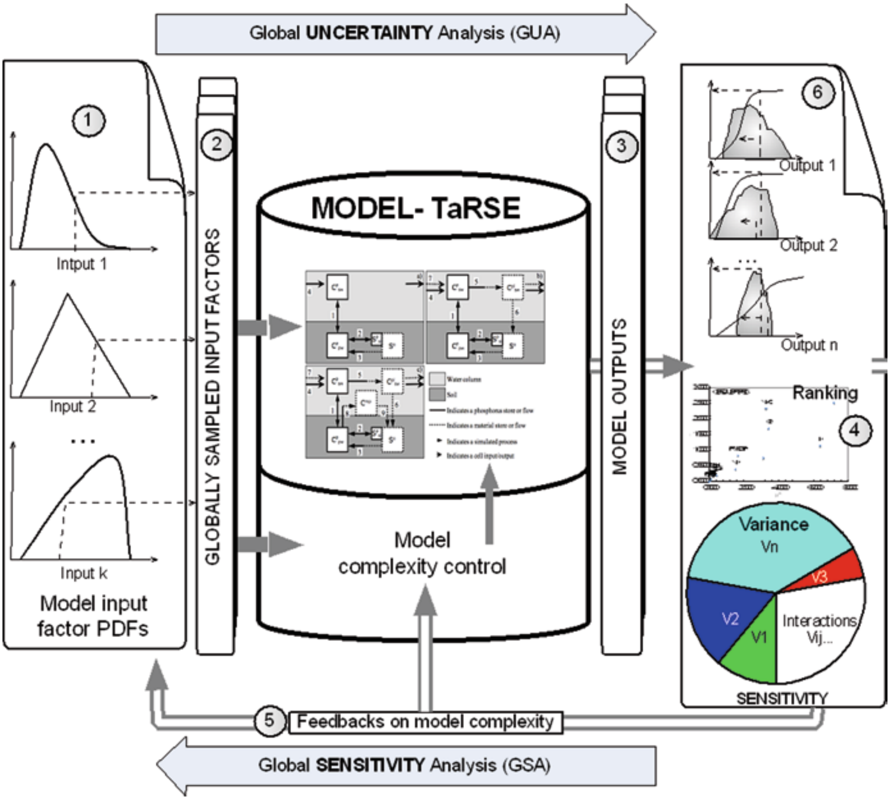

Fig. 4.7 The methodological framework of global sensitivity and uncertainty analysis suggested applied for studying how changing complexity affects the relevance trilemma

4.4 Results

4.4.1 Effects of Model Complexity on Sensitivity

In the context of TaRSE's intended use for managing water quality in the Everglades, concentration of SRP in the surface is the most important output because this has a mandated limit of 10 ppb [48]. Figure 4.8a–c present the Morris method results for this output ($C_{sw}^{\,P}$) at each of the three complexities tested.

As the complexity increased, the relative location of input factors in the $\mu^*\!-\!\sigma$ plane changed. At lower complexities (Levels 1–2) input factors were found closer to the μ^*-axis. At Level 3, the input factors were generally above the 1:1 line and associated with proportionally higher σ-values. Higher σ-values denote greater variability in the elementary effects, and therefore an increase in the role of interactions between input factors, and a converse decrease in the influence of input factors directly on the output.

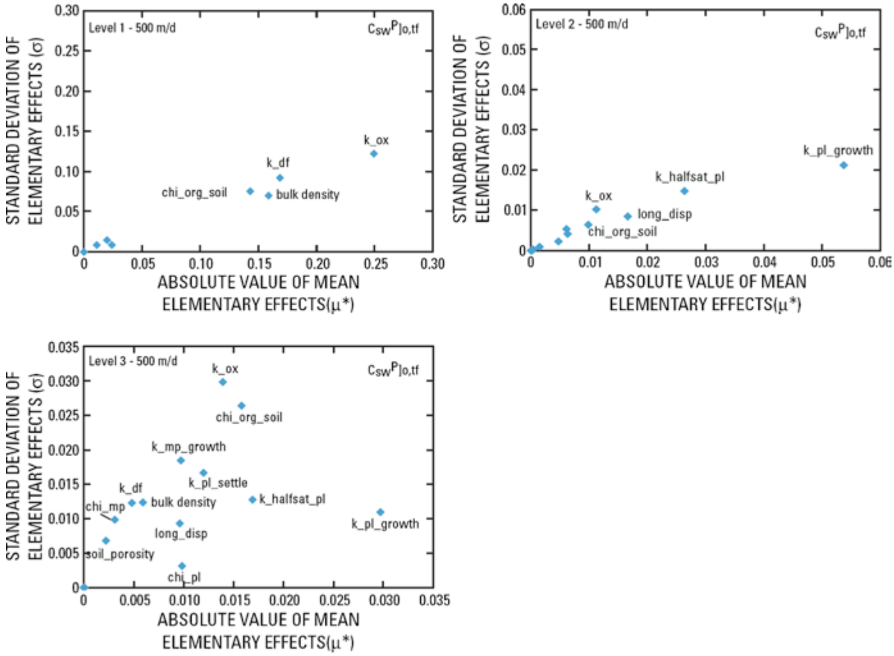

Fig. 4.8 Morris method results for soluble reactive phosphorus in the surface water

As the complexity increased, especially to Level 3, progressively more input factors were drawn out into the $\mu^*-\sigma$ plane. Since the important input factors are distinguished from the unimportant by their relative distance from the origin, this result indicates that more input factors became relatively important as complexity increased, or conversely that fewer input factors were uniquely important. The labeled points in Fig. 4.8a–c represent the input factors deemed "important" according to this method. The number of important input factors was found to increase from 4 in Level 1, to 5 in Level 2, and 12 in Level 3. However, the designation of which input factors are deemed important and which are not is subjectively assigned based on being "close" or "far" from the origin. Furthermore, the proportion of important input factors did not increase monotonically: 4 out of 8 is 50% in Level 1; 5 out of 12 is 42% in Level 2, and 12 out of 16 is 75% in Level 3. Quantitative methods are therefore needed to objectively identify the most important input factors, and to characterize these changes in sensitivity more rationally. Nonetheless, the general observation that the number of important input factors in a model, and the way that they influence an output (directly and linearly versus indirectly and non-linearly) were found to be highly susceptible to relatively small changes (four new input factors) in model complexity for tested input factor ranges.

The sensitivity of C_{sw}^{P} to different input factors at different complexities shows how the role of input factors can change as others are added. In Level 1 we found that k_{ox}, k_{df}, ρ_b, and X_{so} were the most important input factors. For Level 2, plankton in the water column was added to the model, and input factors associated with plankton growth (k_g^{pl} and $k_{1/2}^{pl}$) became the most important, though some of the important input factors from Level 1 (k_{ox} and X_{so}) remained germane. With the addition of macrophytes for Level 3 it became difficult to distinguish the most important input factors. Instead, because of the increased role of interactions, the majority of the model input factors became noteworthy. The lack of any consistency in specific sensitivity to input factors among complexities is indicative of important influences contributed by each increase in complexity. While it may be feasible to calibrate a model to fit surface water phosphorus data without a plankton component, the absence of such a component is questionable if it is so clearly important when included. Similarly, the strong influence of a macrophyte component on the results indicates that the omission of this element would have implications for structural uncertainty.

The quantified results provided by the extended FAST analysis permit a more rigorous evaluation of how complexity affects sensitivity. FAST results for first-order (S_i) and interaction (S_T–S_i) effects for all model outputs are presented in Table 4.4. The input factors of greatest influence to each output are identified with shading. The first-order effects represent the direct responses of an output to each input factor, and the total first-order effect for each output is the percentage of the total variance attributable to direct effects. The remaining percent is that portion of the variance attributable to interactions between input factors. Contributions to variance of particular interactions can be obtained using more rigorous and computationally demanding methods such as the Method of Sobol [50].

Results in Table 4.4 largely corroborate the sensitivities identified in the Morris analysis, though interpretation of the Morris results would appear to overestimate the role of some input factors. This conservativeness is preferred to a method that might underestimate their role, particularly if the Morris method is to be used as a screening tool prior to quantitative analysis by methods like FAST. Once interactions prevailed, essentially from Level 3, it becomes difficult to identify important input factors in Morris for reasons that became very clear in the FAST results—the interactions are so prevalent that many input factors become comparatively important, hence the confusion in the Morris interpretation.

The relative lack of change in overall sensitivity patterns between Level 1 and Level 2 compared with the significant changes seen in Level 3 raise an interesting question: what about the *sensitivity of sensitivity to complexity*? The results of this study appear to demonstrate a nonlinear relationship between sensitivity and complexity, which was also found in Lindenschmidt [27], and drives home the need for more comprehensive global methods to be used when evaluating complex models.

In general, results for all outputs show that the total percentage of variance that can be attributed to first-order effects decreased with increasing complexity (Fig. 4.9a–d). Conversely, the role of interactions, as was suggested by the Morris method results, rose sharply in the most complex case. Note that for the case of C_{sw}^{P}, the total direct effects decreased from Level 1 to Level 2, but the number of important input factors was also reduced from four to two (k_g^{pl} and $k_{1/2}^{pl}$), and their individual contributions to variance increased. Looking only at the total direct sensitivity for C_{sw}^{P}, one would expect non-identifiability to be a greater risk in Level 2, but the relationship is shown to be more complex when the sensitivities to particular input factors are known.

Table 4.4 Results from the extended Fourier amplitude sensitivity test

Output	Complexity level	Input factor k_{df}	k_{ox}	X_{so}^{P}	k_d	θ	ρ_b	λ_t	λ_t	k_g^{pl}	$k_{1/2}^{pl}$	k_{st}^{pl}	X^{pl}	k_g^{mp}	$k_{1/2}^{mp}$	k_{sn}^{mp}	X^{mp}	Total
First order index, S_i																		
C_{sw}^{P}	L1	15.6	36.3	16.1	0.3	0.1	20.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	88.9
	L2	0.7	2.2	1.1	0.8	0.1	0.8	1.1	0.1	50.3	16.2	0.1	0.3	0.0	0.0	0.0	0.0	73.9
	L3	2.2	1.4	2.1	3.4	2.3	2.4	2.6	1.6	9.1	6.3	2.8	2.7	2.5	1.6	1.7	2.7	47.3
C_{pw}^{P}	L1	1.9	43.5	20.9	0.4	1.2	17.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	85.6
	L2	1.6	42.4	19.7	0.3	1.8	17.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	83.2
	L3	1.3	4.5	2.3	1.4	1.0	2.2	1.9	1.3	1.5	1.3	1.4	1.1	13.7	2.4	2.5	9.1	48.8
S^{o}	L1	0.0	98.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	98.7
	L2	0.0	98.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	98.6
	L3	2.4	14.2	2.3	3.3	2.3	2.0	2.6	2.0	2.1	1.4	2.9	2.1	2.1	1.6	6.2	4.0	53.5
S^{P}	L1	1.8	51.3	24.7	0.4	0.1	12.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	90.3
	L2	2.5	49.3	25.5	0.6	0.1	12.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	90.5
	L3	1.4	4.5	2.5	1.5	1.0	1.7	1.8	1.4	1.2	1.4	1.4	1.2	20.1	2.2	2.4	10.0	55.5
C^{pl}	L2	11.1	31.8	11.8	0.2	0.0	10.6	0.6	0.0	20.8	4.5	0.0	7.3	0.0	0.0	0.0	0.0	98.6
	L3	1.8	2.7	1.9	2.2	2.2	1.7	1.8	1.7	5.5	4.9	8.9	8.8	6.2	1.3	2.4	2.7	56.7
C^{mp}	L3	2.0	6.2	4.7	2.6	2.0	1.4	1.4	1.3	1.4	1.5	2.0	2.3	3.0	1.6	7.8	18.5	59.6
Interactions, S_{Ti}–S_i																		
C_{sw}^{P}	L1	4.4	7.6	7.2	0.6	0.3	4.7	0.4	0.4									
	L2	10.3	12.8	8.0	19.0	25.3	24.9	16.8	16.5	16.8	11.7	18.7	15.7					
	L3	73.2	75.8	78.2	74.8	79.3	73.6	73.9	77.1	72.4	78.2	78.6	76.3	64.7	74.4	74.6	70.6	
C_{pw}^{P}	L1	1.2	9.6	5.4	0.6	0.7	4.2	0.6	0.5									
	L2	1.8	6.7	5.7	0.6	0.9	0.6	0.6	0.6	1.0	5.1	0.7	0.7					
	L3	58.0	66.5	48.5	63.3	63.7	56.7	61.6	74.0	73.7	78.4	61.8	59.4	39.8	54.4	76.9	53.5	

(continued)

Table 4.4 (continued)

Output	Complexity level	Input factor																Total
		k_{df}	k_{ox}	X_{so}^{P}	k_{d}	θ	ρ_{b}	λ_{t}	λ_{t}	k_{g}^{pl}	$k_{1/2}^{pl}$	k_{st}^{pl}	X^{pl}	k_{g}^{mp}	$k_{1/2}^{mp}$	k_{sn}^{mp}	X^{mp}	
S^{o}	L1	0.2	1.3	0.2	0.2	0.2	0.2	0.5	0.4									
	L2	0.3	1.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3					
	L3	75.6	71.6	79.4	78.2	62.6	67.2	81.9	82.2	73.2	78.7	73.1	72.5	59.3	64.5	74.2	68.3	
S^{P}	L1	0.7	8.1	5.6	0.5	0.4	2.3	0.4	0.4									
	L2	1.0	7.9	6.7	1.2	0.3	0.6	0.7	0.5	0.5	3.1	0.6	0.6					
	L3	57.7	72.7	53.4	72.3	61.6	54.6	60.8	72.2	69.0	77.2	61.1	59.0	39.5	56.3	74.2	52.8	
C^{pl}	L2	4.1	7.5	5.2	0.7	2.9	1.6	0.7	2.1	0.4	5.0	1.2	0.5					
	L3	69.1	67.0	60.1	61.4	59.2	64.3	68.5	72.1	70.6	65.3	65.0	71.4	58.6	58.3	64.6	61.4	
C^{mp}	L3	63.9	60.1	71.6	69.3	52.1	63.1	64.8	72.6	66.8	77.3	66.2	68.0	66.0	69.5	60.9	60.5	

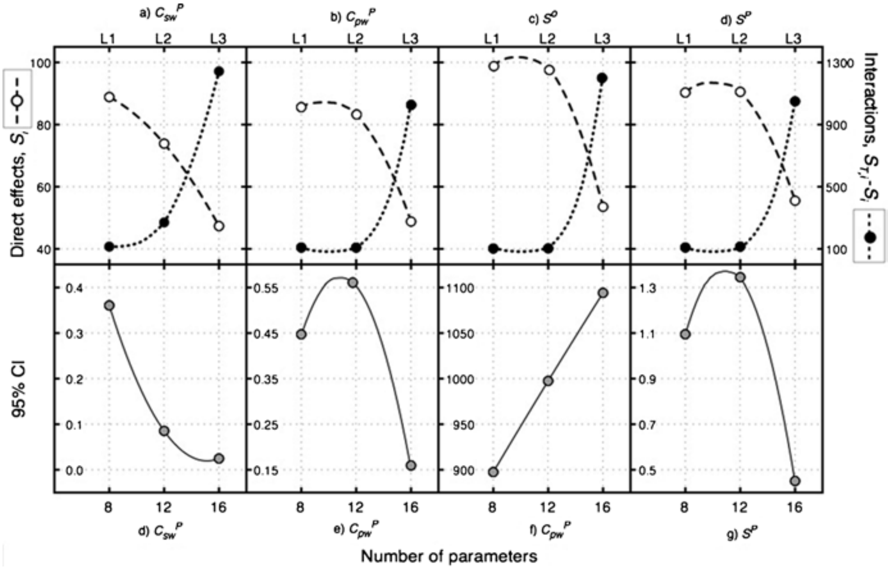

Fig. 4.9 Changes in uncertainty and sensitivity with increasing complexity for state-variables that appeared in all three complexity levels [36]

4.4.2 *Effects of Model Complexity on Uncertainty*

Some of the uncertainty results (Fig. 4.9e–h), presented here using the 95% confidence interval, seem to question the conceptual trends in Hanna [15] (Fig. 4.1a), indicating that these relationships may not be as simple as proposed. In fact, the observed differences are explained by accounting for the fact that some outputs are integrative, meaning that all model components participate in producing their final outcome, whereas others have inherent biases due to the masses and turnover rates of stores. The key output, C_{sw}^{P}, is an example of an integrative output, since it is mechanistically subject to the influence of all other state variables, and the expected reduction of uncertainty holds. By comparison, accreted organic soil (S^{o}) is characterized by a mass that is several orders of magnitude larger than any other outputs or fluxes, and is therefore not integrative. In the case of C_{pw}^{P} and S^{P} we see the uncertainty first rise and then drop, indicating that the relationship between complexity and uncertainty can be non-linear.

Figure 4.10a–c depict the progression of output PDFs across complexity levels for the same key output, C_{sw}^{P}, from a simpler leptokurtic distribution at the lowest complexity level, through the platykurtic distribution at the intermediate level, to a bimodal distribution at the highest complexity.

The bimodality in Level 3 demonstrates the feasible existence of two stable states within the model. The platykurtic shape exhibited by the Level 2 results remained,

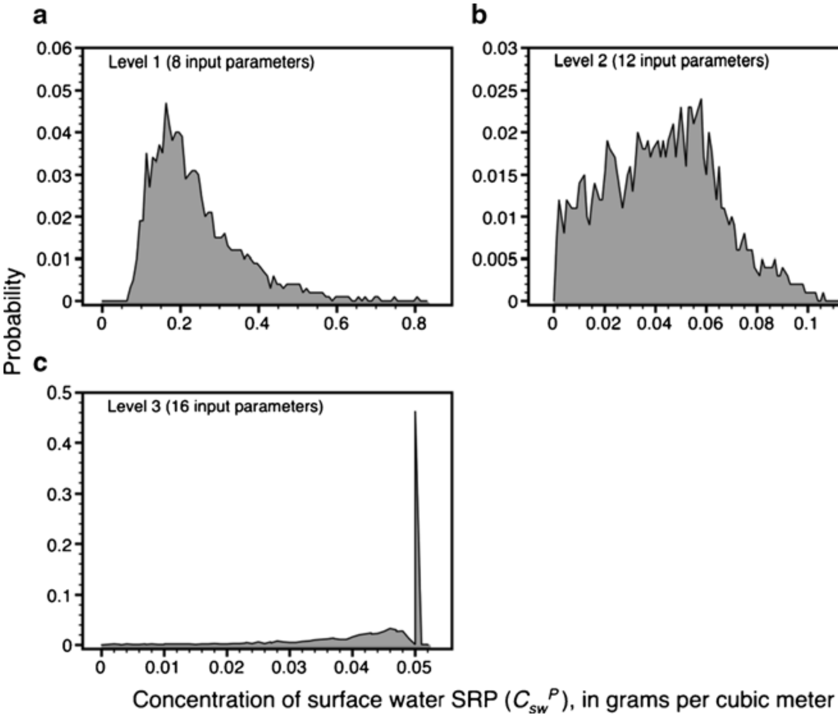

Fig. 4.10 Uncertainty analysis results expressed as probability distribution functions for soluble reactive phosphorus in the surface water using (**a**) complexity Level 1, (**b**) complexity Level 2, and (**c**) complexity Level 3

but a strongly leptokurtic endpoint was also present, and corresponds to combinations of input factor values that push the simulation out of the original stable-state. In this case, the new stable state (the spike) appears as a single value, and indicates that the complexity at this level was sufficient to capture the existence of a second state, but insufficient to capture any variability within the state.

Mechanistically, the presence of this second state demonstrated that a critical threshold existed for the state previously captured in Level 2. Its presence was caused by combinations of input factor values, working in conjunction with initial and boundary conditions, which resulted in the systemic depletion of the biotic components (plankton and macrophytes). This occurred because the range of values over which the input factors were varied was held constant across complexity levels, yet included values appropriate for both of the known stable-states that shallow water bodies can exhibit in the Everglades [3, 46, 47]; namely, algae- and macrophyte-dominated systems [2, 10]. Testing the full range of plankton-dominated conditions in Level 2 presented no problems to the model because the structure was mechanistically appropriate—there were no macrophytes. However, the incorporation of macrophytes into the model introduced a second potential state, but without the necessary feedback mechanisms (i.e., complexity) in place to resolve the extreme conditions produced by combinations of input factor values simultaneously representative of both algae- and macrophyte-dominated conditions. Without phytoplankton there was no surface-water sink for phosphorus (uptake by phytoplankton), and ${C_{sw}}^{P}$ continuously input at the boundary remained essentially unchanged in these cases, depicted by the spike in outflow values matching the boundary concentration of 0.05 g/m^3.

The platykurtic area represents model conditions under which the input factorization of the system did not catastrophically overwhelm it. The results therefore mimic those of Level 2, where macrophytes were absent and phytoplankton dominated the surface-water phosphorus dynamics. It is noteworthy that the introduction of macrophytes still acts as a phosphorus sink in these cases, stressing the phytoplankton in terms of phosphorus availability and thereby dampening the frequency of lower ${C_{sw}}^{P}$ values (a sign of greater phosphorus uptake due to growing plankton). Macrophytes also prevent the majority of ${C_{sw}}^{P}$ results from exceeding the boundary input concentration (which can only occur when significant diffusion takes place due to high ${C_{pw}}^{P}$), as in Level 2, and as was never the case for Level 3 because of porewater SRP uptake by the macrophytes [18].

4.5 Conclusions

Modeling is an art because it is an uncertain science. This uncertainty is increasingly attended to by modelers and managers, and is of growing concern to the public [40]. As the complexity of our problems grows we are likely to find ourselves more reliant on more complex models for some modicum of insight into scenarios beyond our ability to experimentally or intellectually assess. Integrated environmental assessment and management in response to climate change must rely on relevant models that can answer the appropriate questions with acceptable uncertainty.

When developing or applying such models there are many important questions to be addressed: What processes should be added? How does this impact uncertainty? Can the real system behavior be modeled? Will the model be usable based on available knowledge of the system? To answer some of these questions in an objective way, and to add transparency and guidance to the process of navigating model development and uncertainty, a relevance framework is suggested based on the trilemma among complexity, uncertainty, and sensitivity. A methodological framework based on global sensitivity and uncertainty analysis proved useful for objectively exploring and characterizing the relevance trilemma.

Application of the proposed framework to a case study allowed for the systematic evaluation of the effect of increasing model complexity on the model relevance. Firstly, in this application direct effects of input factors on output sensitivity were observed to decrease with complexity, while interactions increased. Both the number and identity of important input factors was found to change in complicated ways with the addition of complexity. Uncertainty was found to decrease with increasing

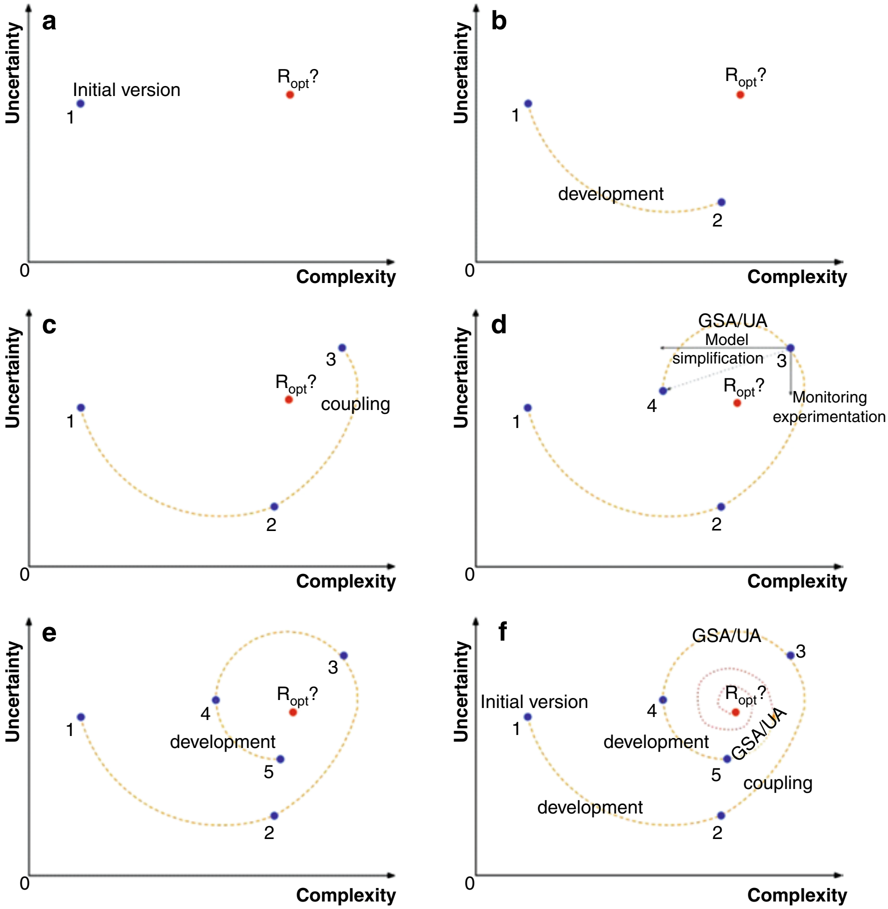

Fig. 4.11 Model development framework to achieve optimal model relevance (R_{opt}) through exploration of sensitivity-uncertainty and -complexity tradeoffs

complexity for some state-variables, including the key system variables (like surface water reactive phosphorus in the Everglades example), but increased for others, indicating that the relationship between complexity and uncertainty is not as simple as the Hanna et al. [15] conceptual relationship would indicate. Distinct shifts in the output PDFs were observed, including the emergence of bimodal states in the model output. These alternative system states might be a true expression of the ecological system response and therefore desirable (and a driver) of the introduction of the increasing complexity of the model.

From a practical perspective, the proposed GSA/UA tools could inform model development to achieve optimal relevance (R_{opt}), following the pattern presented in Fig. 4.11. From an initial model version (Fig. 4.11a), developers seek a reduction in output uncertainty by refining the description of model components and the inclusion of additional factors; e.g., increased complexity (Fig. 4.11b). In the context of exploring adaptation strategies to climate change, the model is then coupled with other climatic, environmental, or socioeconomic models to create an integrated tool that allows the developer and users to answer some of the pertinent questions. Model coupling thus increases the relevance of the resulting model at the cost of increased complexity and possibly uncertainty (Fig. 4.11c). At this stage, formal GSA/UA informs the developers about opportunities to simplify the model for components that at the scale of integration might no longer be important, or identify important components of the integrated system that require monitoring or experimentation to in turn lead to a better description and a reduction in output uncertainty (Fig. 4.11d). Through user and developer interactions, this path is followed until an accepted model relevance is achieved for the purpose of the problem being studied ($R_{opt.}$) (Fig. 4.11f). Although this is likely an open-ended process, endpoints are achieved through risk analysis, negotiation, and limitations introduced by available resources (e.g., time, model development cost, monitoring and experimentation cost).

One of the motivations for the NATO meeting resulting in this work was recognition of the rapid pace at which conversation has shifted from the question of climate change to the adaptation to climate change, and the "risk of putting the cart in front of the horse" on this issue. The same might be said of our modeling technology in support of these questions. We continue to rapidly increase the complexity of our models without always acknowledging, rarely studying, and not yet fully understanding the profound implications complexity has for the uncertainty associated with their results. In general, the concurrent and systematic evaluation of the global sensitivity and uncertainty of the model during the development process can help elucidate the general patterns introduced by the effects of increasing model complexity, and thus should become a central part of the integrated modeling practice.

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Chapter 5
Multiple Dimensions of Vulnerability and Its Influence on Adaptation Planning and Decision Making

L.D. Mortsch

Abstract Adaptation is an adjustment in natural or human systems that moderates harm or exploits beneficial opportunities from climate change. Well-informed adaptation planning and decision making require information that extends beyond the natural domain to the human dimensions of climate change. Understanding the sensitivity to climate of people, communities, economic activities, or regions as well as the capacity to adapt provides insights into vulnerability or the potential for loss. This chapter explores vulnerability assessment and its influence on adaptation. First, a review of two chapters from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) provides background on vulnerability at the global and regional scale. The criteria developed to define vulnerabilities as "key" and the resultant regional vulnerabilities are reviewed. Water resources, food supply, coastal areas, human health, and ecosystems consistently emerge as vulnerable sectors. The section on North America demonstrates that developed countries have vulnerabilities to climate change—as well as adaptive capacity and adaptation challenges—not just developing countries. Examples are drawn from marine coastal areas. Next, the chapter reviews conceptualizations of vulnerability assessment from the natural hazards and climate change fields. These insights are applied in a case study of urban flooding in downtown London, Ontario, Canada, in the Upper Thames River Watershed. Three approaches are used to map vulnerability: natural hazards analysis, emergency preparedness planning, and adaptive capacity assessment. The adaptive capacity approach uses three quadrants of a vulnerability domain

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that considers internal socioeconomic and biophysical properties that make a system vulnerable as well as external biophysical factors acting upon the community. It assesses those human dimensions that affect the ability to cope with and respond to flooding. These approaches to framing and assessing vulnerability provide different information to the adaptation planning and decision making process. Designing robust adaptive responses requires broader consideration of the dimensions of vulnerability and improved understanding of the factors shaping vulnerability—particularly the human dimensions—in order to increase resilience in light of a changing climate.

5.1 Introduction

While mitigation—reducing emissions of greenhouse gases and increasing sinks—has been the leading response to climate change, there is growing recognition that adaptation, responding to the impacts and opportunities of a changing climate, is a necessary and complementary response. In its Fourth Assessment Report (AR4), the Intergovernmental Panel on Climate Change (IPCC) indicated that "[a]daptation will be necessary to address impacts resulting from warming which is already unavoidable due to past emissions" [31]. The IPCC assessment not only determined that "…warming of the climate system is unequivocal…" [32], it also attributed most of the increase in average global temperatures since the 1950s to the observed increase in anthropogenic greenhouse gas concentrations [33]. In addition, there is emerging evidence that "…anthropogenic warming has had a discernible influence on many physical and biological systems" [31]. Effects on human systems are being detected but the influence of other interacting stresses and adaptation make attribution to warming less robust [56]. Projections of global temperature increases range from 1.1°C to 6.4°C (2090–2099 relative to 1980–1999) [33]. Looking to the future, people, economic sectors, regions, communities, and ecosystems will need to adapt to a changing climate as well as the evolving impacts [30].

Adaptation is an adjustment in natural or human systems in response to actual or expected changes in climate or to the impact of those changes. The goal is to moderate harm or exploit beneficial opportunities. Adaptation has been described as anticipatory or reactive, autonomous or planned, and private or public. In natural systems, adaptation is likely to be reactive and autonomous with respect to the stresses or opportunities brought about by changing climatic conditions. However, in human systems and managed ecosystems, there is the prospect of undertaking anticipatory, planned, private, or public adaptation [47]. These forms of adaptive responses acknowledge that changes in climate are likely, that the magnitude and rate of change are likely to increase, and that the attendant stresses due to a changing climate are likely to intensify over time. Climate change information needs to be explicitly considered. But well-informed adaptation planning and decision making require information beyond the natural domain and must include the human dimensions of climate change. It must understand the sensitivity to climate of people, communities, economic activities, or regions as well as the capacity to adapt. One needs to understand vulnerability. Without this perspective, insufficient actions or actions that inadvertently increase vulnerabilities may be taken.

Vulnerability is a key, multidimensional idea in human-environment research. Its conceptualization has developed over time [11, 12, 15, 16, 17, 28, 35] and reflects contributions from various bodies of scholarship including global environmental change [42], engineering [26], anthropology [10, 20], hazards and disaster studies [4, 8, 13, 14, 15, 34], and climate change [18, 23, 36, 37, 61, 66]. See McEntire [43] for a good review from a disaster reduction perspective. As a result there are competing and often contradictory definitions; broadly, *vulnerability* refers to "the potential for loss" [11, 50, 51] which comprises exposure and susceptibility to losses.

One IPCC definition of vulnerability to climate change is the:

> …degree to which a system (geophysical, biological and socioeconomic) is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes [58].

Vulnerability (V) has been expressed as:

$$V = \text{Exposure} + \text{Sensitivity} + \text{Adaptive Capacity}$$

However, vulnerability has been conceptualized more broadly in the IPCC. Vulnerability also can refer to a vulnerable system, the impact to this system, or the mechanism causing these impacts [58].

This chapter explores how the framing and assessment of vulnerability (and its metrics) influence adaptation: the adaptive responses that are formulated, evaluated, and ultimately implemented. In climate change assessment for adaptation decision making, there is a need to expand beyond understanding exposure or the physical factors that contribute to vulnerability. There is a need to understand the human dimensions that contribute to vulnerability. For example, what interacting social, economic, and political factors create a context from which vulnerability emerges? What attributes enhance or diminish the capacity to adapt and hence vulnerability? How can an understanding of vulnerability inform the development of measures aimed at increasing resilience and facilitating adaptation? Robust adaptation decision making requires these broader considerations.

Ideas on vulnerability and adaptation are explored in the following manner in this chapter. First, two chapters from the IPCC AR4 provide perspectives on vulnerability at the global and regional scales. The criteria for framing vulnerability developed by Schneider et al. [58] are reviewed and some of the resultant key vulnerabilities are summarized. The chapter on North America demonstrates that developed countries have vulnerabilities to climate change—as well as adaptive capacity and adaptation challenges—not just developing countries [19]. Issues specifically related to marine coastal areas are highlighted. Next, the theoretical and methodological underpinnings of vulnerability assessment from the natural hazards and climate change fields are reviewed. How the perspectives from these different fields influence the development of vulnerability indicators is presented. Integration of the biophysical, societal, economic, policy, and environmental dimensions is important.

A case study of downtown London, Ontario, Canada, in the Upper Thames River watershed, explores increased exposure to urban flooding due to climate change. Vulnerability is mapped from a hazards, emergency preparedness, and adaptive capacity approach. These approaches serve to illustrate the different information that emerges from the assessment process and how that may influence adaptation decision making.

5.2 Vulnerability in the IPCC AR4

5.2.1 Key Vulnerabilities Identified in the IPCC AR4

Schneider et al. [58] in Chap. 19 "Assessing key vulnerabilities and the risk from climate change," integrated information on climate system changes with impact and adaptation information from sectoral and regional chapters to provide a global perspective on "key" vulnerabilities. Cataloguing key vulnerabilities informs mitigation and adaptation decision making. For mitigation, these vulnerabilities assist policy makers in establishing targets for greenhouse gas concentrations in the atmosphere. The objective of greenhouse gas stabilization as outlined in Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) is to "… prevent dangerous anthropogenic interference with the climate system." Assessment of key impacts—their magnitude, persistence, or scope—help resolve the levels of greenhouse gases and rates of climate change with serious or irreversible consequences. This information is relevant for adaptation decision making but additionally the IPCC assessment tries to identify the adverse impacts on people, places, and activities. Determining key vulnerabilities helps decision makers assess levels of risk, develop relevant adaptation strategies, and set priorities for action [58].

Seven criteria were used to select key vulnerabilities in market, social, geophysical, and ecological systems as well as regions and peoples. They included:

- Magnitude (scale and intensity) of impacts
- Timing or immediacy of impacts
- Rates of change, exceedance of thresholds, persistence, and irreversibility of impacts
- Likelihood of impacts and vulnerabilities (probability of an outcome having occurred or occurring in the future) and confidence in their assessment
- Availability and feasibility of effective adaptations (or adaptive capacity)
- Distributional effects and equity issues
- Importance of system (or system properties) at risk [58]

These criteria are also useful for assessing vulnerabilities at smaller scales, such as a country, region, or watershed. This framework can also inform the setting of priorities for adaptation strategy development and implementation.

The assessment identified systems such as food supply, infrastructure, human health (heat, disease, and air pollution), ecosystems, and water resources as having notable key vulnerabilities. Issues of migration and conflict were also projected to

Table 5.1 Key regional vulnerabilities from a global perspective [58]

Region	Issues/Risks
Africa	Food security, agricultural productivity (subsistence agriculture), water stress, human health (malaria), ecosystem effects
Asia	Water stress, agricultural productivity, floods and droughts, human health (cholera), coastal damage
Latin America	Water stress, coastal damage, infrastructure, ecosystem effects
Polar (Northern) Regions	Already experiencing adverse effects of changes in climate on ecosystems and society
	Loss of tradition, culture, communities
Small Islands	Already experiencing negative effects of climate change
	Sea level rise, storm surge, coastal damage, agricultural productivity, water supply and quality, infrastructure
	Long-term sustainability of societies
Europe	Water stress, flooding, human health (air pollution, heat stress)
North America	Water stress, flooding, human health (air pollution, heat stress)
Australia and New Zealand	Water stress, wildfires, human health (air pollution, heat stress)

intensify due to relocation of peoples due to water shortages, coastal and riverine flooding, and droughts. The uneven distribution of impacts and limited potential to adapt is concentrated in selected socioeconomic groups and raises issues of equity and distributive justice. The poor, elderly, young, infirm, and indigenous in resource-dependent communities were identified as most vulnerable.

Schneider et al. [58] carried out a comparative assessment of regional vulnerability from a global perspective; these key vulnerabilities are summarized in Table 5.1. Africa was the region likely to be most affected by climate change but small island states, and Southeast Asia, are also likely to experience high vulnerability. Vulnerability in two sectors—water resources and coastal areas—emerged across many regions. Densely populated and developed coastal areas are highly vulnerable due to their exposure to sea level rise and attendant flooding. Water resources vulnerability is highly complex. In part, it is interlinked with regional variation in resource availability and quality, and socioeconomic and cultural factors influencing demand, access, development, and adaptive capacity [58].

Harm from climate change can be reduced by adaptation and there are a wide range of accessible, feasible, and effective adaptation options. However, there are challenges; they include developing the capacity to assess impacts and vulnerabilities, identify and implement new adaptations, and overcome inertia in systems. In some cases, there may be limits to adaptation [58]. Biological systems are adaptable; however, there may be no options to preserve endemic species whose habitat is threatened by climate change. Similarly, a rapid rate of change could exceed the capacity of natural systems to adapt (and human systems as well). While low-lying, densely populated coastal areas are very vulnerable to the effects of sea level rise and more intense storms, there are some options (although the economic costs and environmental effects may be high) for averting the impacts. In managed systems such as agriculture and water resources, there may be a broader range of options to adapt to a changing climate.

5.2.2 North America Is Vulnerable to Climate Extremes and Climate Change

Based on the previous section, which identifies key global vulnerabilities to climate change [58], one might presume that people and activities in developed regions such as Europe and North America are not especially vulnerable to climate change. On the whole, these regions are wealthy, with a highly educated population; access to technology, information, and capital; extensive infrastructure; and robust, mature institutions and political systems. These attributes contribute to high adaptive capacity, giving these regions a high likelihood of successfully responding—i.e., adapting—to the projected changes in climate and associated impacts and opportunities. However, developed countries also have vulnerabilities and adaptation challenges. Perhaps the determinants of vulnerability and barriers to adaptation are different. In developing countries, the limits to adaptive capacity may be related to poverty, education, governance, and access to capital. In developed countries, beneficial attributes may also be liabilities for adaptation. This includes: extensive infrastructure, highly managed systems, stable institutions and policy processes, and established codes and standards.

The assessment of North America for the IPCC AR4 demonstrated that North America is vulnerable to current climate variations and extremes. Historically, the adaptive capacity in North America has not always protected people and property and the environment from climate-related extremes such as riverine flooding, storm surge, and drought. This adaptation deficit, in combination with other factors, has contributed to significant disruptions [19].

As we assess the future potential to adapt to climate change in North America, we have to consider important regional and socioeconomic variations in sensitivity to climate changes, adaptation options, and adaptive capacity [40, 41, 48]. North America has people, communities, activities, infrastructure, and livelihoods that are vulnerable. Issues related to coastal areas illustrate some of the vulnerability and adaptation problems.

5.2.2.1 Marine Coastal Areas

Sea level is projected to rise along many coasts of North America due to climate change. In arctic regions, ice cover and permafrost are also likely to decline. These climate-related changes interact with other physical processes increasing exposure of coastal areas to progressive inundation, storm-surge flooding, and shoreline erosion [19]. Exposure is enhanced by a potential increase in the frequency, duration, and intensity of storms. At present, many coastal areas are not adapted to these hazards and readiness for increased exposure is poor [19].

Coastal areas offer high amenity value. In the remote north, many coastal settlements have been sited for their access to the sea and its natural resources. In southerly areas, there is an ongoing impetus for development and population growth in

Canada (e.g., southern British Columbia, Gulf of St. Lawrence, and selected reaches in Atlantic Canada) and the U.S. (e.g., northeast U.S. seaboard, Florida, the Gulf of Mexico, and California). These social and economic pressures enhance vulnerability by increasing the value of property at risk and number of people exposed [22, 54, 60]. The challenges of adapting become more complex with more high-value development and intensification of land use. These pressures can lead to maladaptation—allowing development in hazardous areas.

Development also limits the potential for natural ecosystems to respond to rising sea levels. Ecosystem adaptation relies on unconstrained natural processes such as accretion of sediments to keep pace with rising sea levels and landward migration. Coastal wetland ecosystems can be caught in a coastal squeeze if human development and hardening of the shoreline affect natural processes and impede migration [19].

In coastal areas, generic options for adapting to sea level rise and enhanced storm and erosion exposure include:

- Protection—includes physical reinforcement of the shoreline either by hard measures (sea walls, riprap, groynes) or soft measures that enhance natural protection (vegetating coastal dunes)
- Accommodation—involves constructing structures in ways that minimize damage (e.g., by placing buildings on elevated pylons) or developing land-use and zoning plans that limit the type of structures along the shoreline (e.g., port facilities or fish-processing plants or recreation) while prohibiting others (such as private residences)
- Planned retreat—recognizes the inexorableness of coastal processes such as erosion and elects to abandon areas closest to the shoreline or locate only temporary or expendable structures in these areas [49, 64]

However, adaptation can be constrained by circumstance. Shishmaref, Alaska, a northern indigenous community of about 550 people, was located on a small barrier island. Exposure to wave and storm surge erosion had been enhanced by a reduction in sea ice extent and thawing of permafrost; buildings and critical infrastructure were threatened. While the initial response of the community was to protect with riprap and sea wall construction, the town has since relocated to the mainland. This involved a lengthy process of planning, organizing, garnering support for, and implementing the relocation (http://www.shishmarefrelocation.com/index.html). In contrast, the settlement pattern in highly developed, urban coastal areas of North America may have limited options for relocating due to the significant investment in buildings and other infrastructure as well as the cost and challenge of displacing people.

5.2.2.2 Adaptation in North America

Much ongoing adaptation is based on experience. For example, the design and administration of water resources management (e.g., flood management and water allocation) and coastal zone management (e.g., setback regulations in coastal areas) systems are predicated on experience. Yet, extreme events often expose an adaptation deficit. Many of the impacts associated with Hurricane Katrina were the result of a failure of adaptation. Infrastructure such as the levees encouraged development and created a false sense of security. While there were good forecasts on hurricane landfall and communications for evacuations, there were deficiencies in evacuation plans, particularly with respect to the capacity to respond in many of the poorer sections of cities [67].

A fundamental assumption—stationarity—is being challenged in light of climate change with implications for resource management [45]. Information about future climate states, particularly changes in variability or events that exceed historic norms, needs to be integrated into planning and management. However, decision makers and practitioners often lack the necessary guidance and tools to assess vulnerability and associated risks in light of climate change and the uncertainty associated with it. The high adaptive capacity of North America is an asset for coping with or benefiting from climate change. "Capacity, however, does not ensure positive action or any action at all" [19]. Adaptation needs to be facilitated and one means is to develop information that supports decision making and guides action.

5.3 Assessment of Vulnerability: A Case Study

The Upper Thames River Watershed in London, Ontario, Canada, illustrates how conceptualization of vulnerability influences adaptation planning and decision making. This case study explores vulnerability to an increase in urban flooding due to climate change from the fields of natural hazards and disaster management and climate change assessment. Maps are generated using the different approaches from these fields to illustrate the type of information available for adaptation decision making.

5.3.1 Approaches to Vulnerability

Approaches to vulnerability have evolved over time. Natural hazards and disaster studies traditionally focused on the biophysical aspects of vulnerability. Topics of interest included exposure to a hazard, distribution of hazardous conditions, number of people and structures affected, estimation of potential damage costs, and identification of adjustments available to individuals and society [7, 14]. A more recent conceptualization asserts that vulnerability is socially constructed. Social vulnerability explores the ability or inability of individuals or groups to anticipate, cope with, resist, and recover from or adapt to any external stress (e.g., flooding) [5, 15, 36, 46]. Social-demographic characteristics such as age, socioeconomic status, gender, race, and wealth influence vulnerability instead of physical factors. The next formulation, "vulnerability of place," integrates the physical hazards with the unique socioeconomic and geographic context of place [14]. Researchers identify high-risk areas, but more importantly they identify vulnerable populations. They are keenly interested in what causes people to be vulnerable, what measures can reduce vulnerability [5], and how to help and empower those who are most vulnerable [28].

In the hazards and disaster field, it was recognized that emergency management systems had to be reoriented. They had to become more proactive and emphasize reducing losses (life and property) and future hazard impacts through mitigation, preparedness, response, and recovery rather than focusing on reactive rescue and post-event cleanup. The degree to which a population was vulnerable to hazards was not dependent solely on the exposure to the hazard but also the social, economic, and political factors that influence people and communities. Access to economic, social, or political resources is fundamental to adaptation. Due to disparities in wealth, socioeconomic status, and housing, some population subgroups (individuals, households, or communities) have a disproportionate exposure to hazards as they have less ability to adapt, cope, or respond.

In the climate change context, vulnerability is the degree to which a system is susceptible to or unable to cope with adverse effects of climate change, including variability and extremes. It is a function of the magnitude and rate of change as well as exposure, sensitivity, and adaptive capacity [61]. Climatic variability and extremes, and a suite of socioeconomic characteristics are interwoven to produce patterns of vulnerability and adaptive capacity. Climate vulnerability is an undesirable state of risk while climate adaptation engenders changes in systems or behavior to diminish vulnerability [20]. Adaptation relies on human and financial capital (knowledge and money) and changes and readjustments in social organization (investments in social and political capital) to reduce vulnerability [5].

This case study builds upon Füssel [23] and others [12, 14, 15, 21, 66] to develop a conceptual framework to assess vulnerability in the Thames River watershed (see Fig. 5.1). Four dimensions of vulnerability are identified and relate to scale—conditions that are internal or external to the system/community and domain—socioeconomic or biophysical characteristics. This study explores three quadrants of the vulnerability domain—the internal socioeconomic and biophysical properties that make a system or community vulnerable and the external biophysical factors acting upon the community. Here, the external biophysical domain is urban flooding hazard, which is depicted by mapping new floodlines associated with the climate scenarios. The internal biophysical domain characterizes the infrastructure (e.g., housing stock) that gives rise to situational vulnerability. The internal socioeconomic domain is represented by socioeconomic indicators that help to explain the capacity to adapt to urban flooding. The external macro-level issues related to social structures, economics, political structures, and organizational conditions acting on the community represented in the external socioeconomic sphere are not considered.

Indicators have been used to develop a better understanding of the socioeconomic and biophysical factors contributing to vulnerability. Indicators can be developed at multiple scales (e.g., household, census area, state) and the characteristics often coincide with determinants of adaptive capacity [2, 14, 53, 65]. Indicators are mapped using Geographic Information Systems (GIS). GIS allows for the monitoring

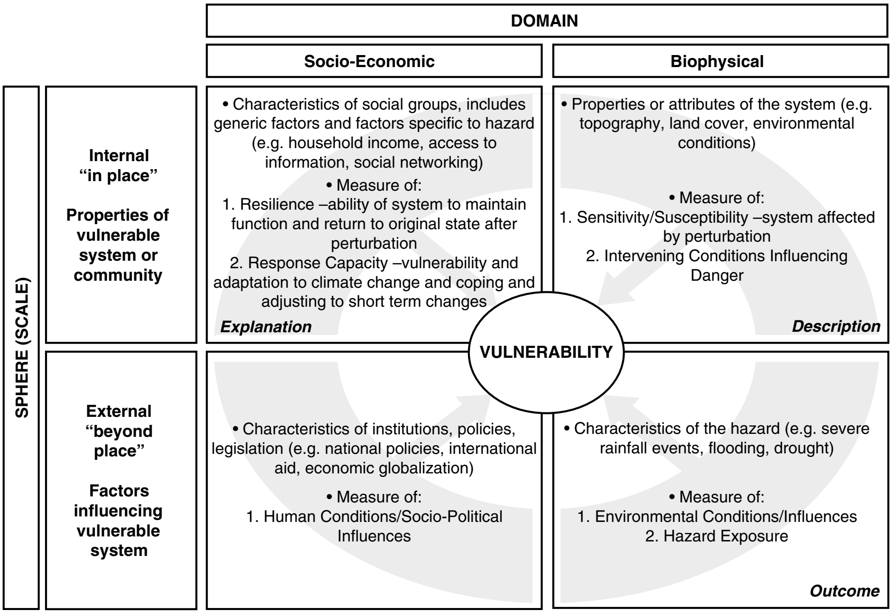

Fig. 5.1 Four dimensions of vulnerability [23, 27]

of vulnerability over time and space, identifying hot spots requiring adaptation policies, developing an understanding of the processes underlying vulnerability, developing and prioritizing adaptation strategies to reduce vulnerability, and determining the effectiveness of those strategies [57, 65].

5.3.2 Upper Thames River Watershed

The Upper Thames watershed is located in southwestern Ontario, Canada (Fig. 5.2a). There are two main branches of the Thames River in a watershed that extends 3,432 km^2 (Fig. 5.2b). Agriculture (78%) and forested land (12%) dominate the watershed, with 9% of the land in urban use. The watershed has a population of 485,000, with the majority living in the City of London [63]. This study focuses on the Forks of the Thames, the confluence of the north and south branches of the Thames River near the center of the City of London (Fig. 5.2c).

5.3.3 Assessing Vulnerability in the Upper Thames Watershed

Climate change, due to rising concentrations of greenhouse gases, is very likely to increase the intensity of precipitation, enhancing the potential risk of flash flooding in urban areas and increasing community exposure to this hazard [3, 6, 29, 38, 44].

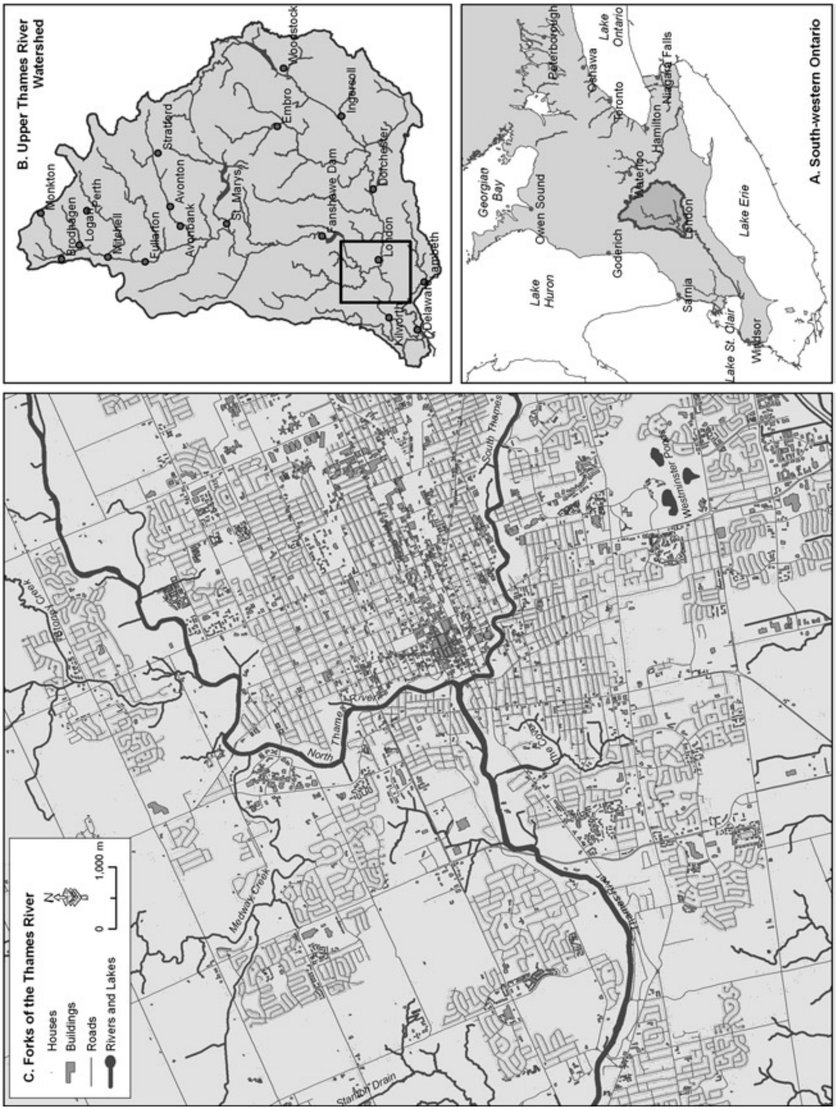

Fig. 5.2 The Forks of the Thames study area, located in the Upper Thames Watershed in southwestern Ontario

Future flood damage from more intense precipitation events will depend on the capacity of populations and communities to adapt. The vulnerability assessment in the Upper Thames watershed examines the changing exposure to riverine flooding in an urban area due to climate change scenarios, and the socioeconomic and physical attributes of place that influence the capacity to adapt (reduce the impacts of flooding). The detailed methodology is provided in Hebb and Mortsch [27].

5.3.3.1 Natural Hazard Analysis

Within the climate change context, this analysis explores the potential increase in exposure to flooding hazard due to an increase in precipitation. Exposure to the physical hazard is described as the distribution of the hazardous condition and the people and structures affected. One Global Climate Model (GCM) simulation and a modified *K*-nearest-neighbor (*K*-NN) non-parametric weather generator were used to develop a wet climate change scenario [59]. For the flooding assessment, precipitation events representing annual maximum daily rainfall were input to the hydrologic model to determine the corresponding peak flows [55]. A large number of event storms were run, so that a flow frequency analysis could be performed and return periods determined. A hydraulic model was used to convert flood flow into water elevation for floodplain mapping of the Forks of the Thames River area. In this exploratory research application, only one GCM simulation was used to develop the climate change scenario for input to the hydrologic simulations and assessment. However, in the case where actual real-world planning and decisions were to be made, many more climate change scenarios should be developed and incorporated into the assessment process.

The climate change scenarios run through the hydrologic and hydraulic models provided the information to define "new" flooding conditions spatially through GIS. The 100-, 250-, and 500-year floodlines were selected for mapping because of their relevance to planning in the region. The 100-year flood is used to separate the flood fringe from the floodway and the 250-year flood is used to define the floodplain or hazard area. The 500-year flood represents the most extreme condition used for disaster planning. The floodplain mapping for the wet climate change scenario in Fig. 5.3 shows the area exposed to flooding. The areal extent of the 100-, 250-, and 500-year floodlines expanded in comparison to floodplain mapping based on historical conditions. The number of people and structures exposed also increased. The areas behind the dykes in the Forks of the Thames region will likely be breached in the 1-in-100-, 250-, and 500-year floods. In fact, the generated floodlines show that the dykes are breached by the 1 in 50-year flood (not shown). The north branch of the Thames River was the most flood-prone, with the largest area flooded in the vicinity of the Forks of the Thames River on the western bank. The majority of homes exposed to flooding were located behind a series of dykes built along the Thames River that were breached by the 100-, 250-, and 500-year return period floods. The new hazard/exposure developed from the climate change scenarios (and hydrologic and hydraulic modeling) and delineated by the new floodlines was used as input for the subsequent vulnerability assessments.

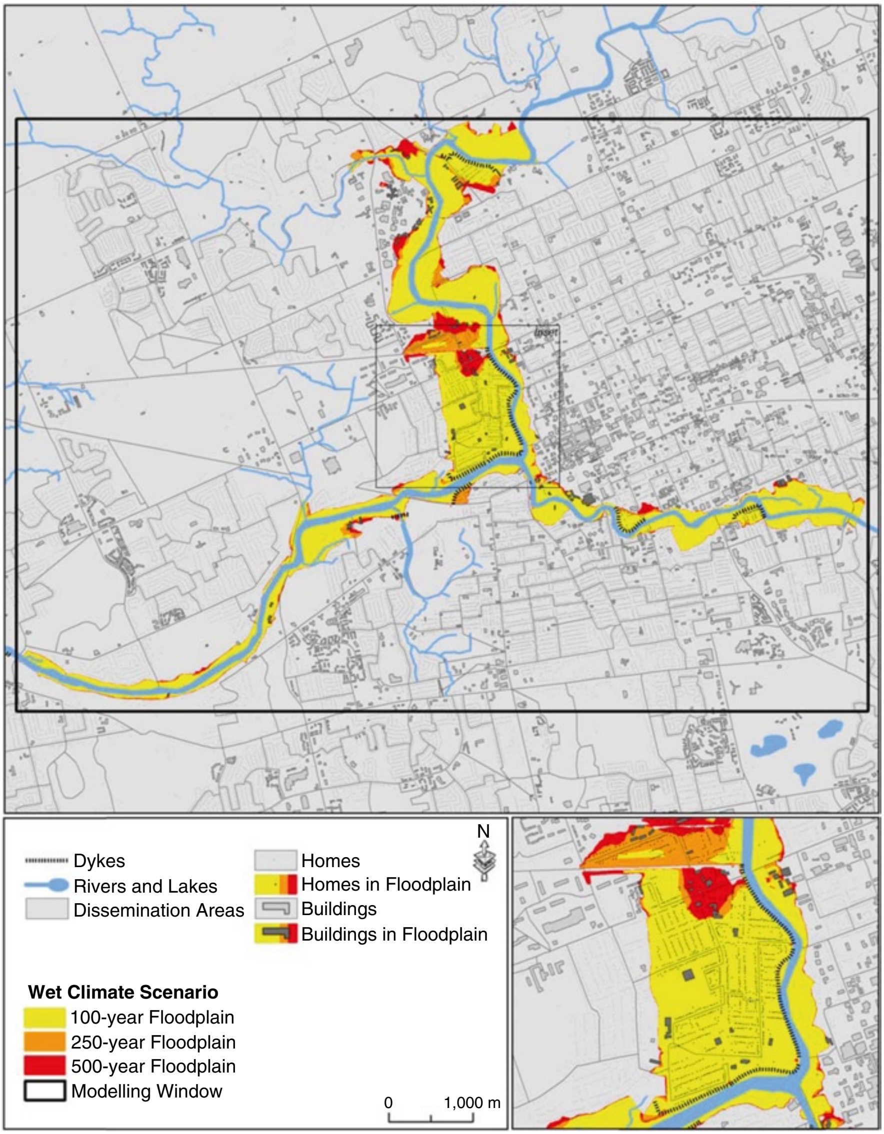

Fig. 5.3 Flood hazard lines under the wet climate scenario in the Thames River in downtown London, Ontario, Canada

5.3.3.2 Emergency Preparedness Planning

The emergency preparedness approach within the climate change context assesses the infrastructure that is vulnerable to damage (e.g., roads, bridges, and water and sewage treatment plants) and the emergency infrastructure (e.g., evacuation routes, buildings for housing evacuees) that could be affected. The mapping showed that

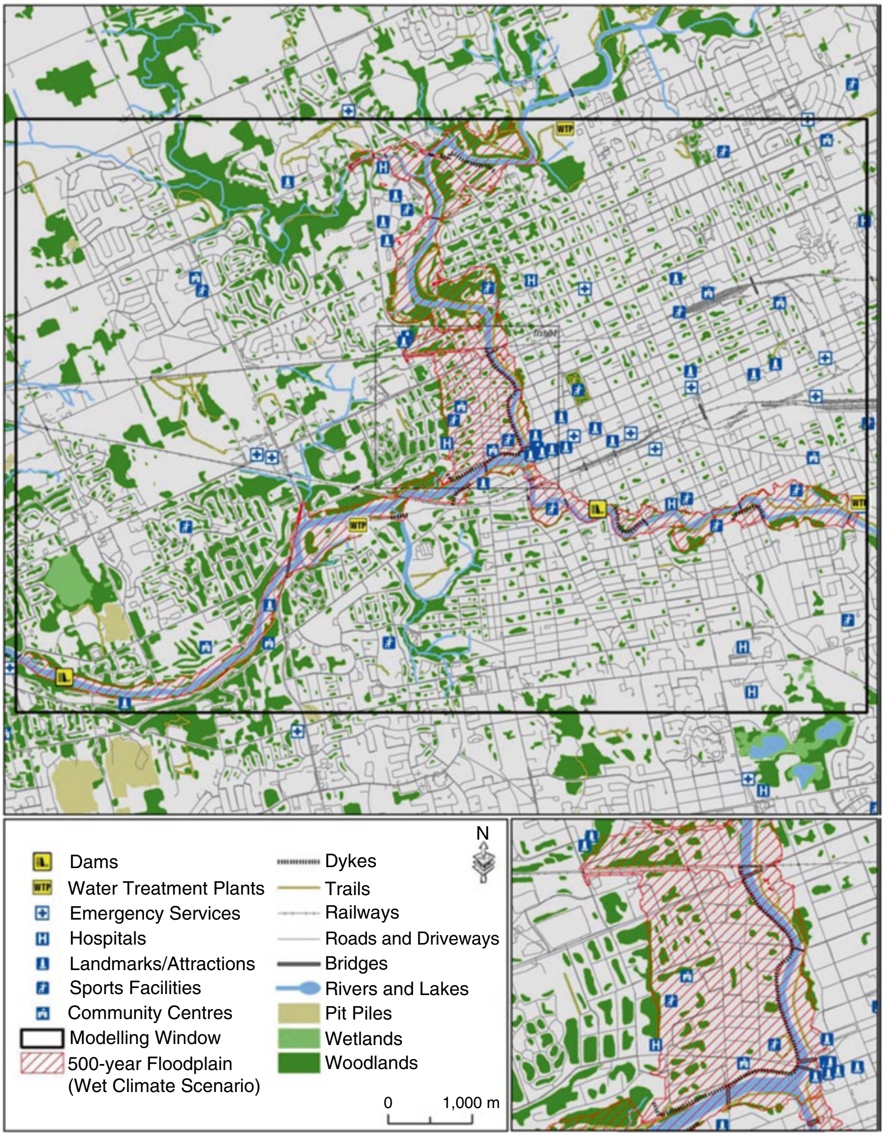

Fig. 5.4 Infrastructure exposed to the 500-year floodline under the wet climate scenario in the Forks of the Thames

some infrastructure (roads, railway lines, bridges, pollution control plants) and recreational resources (trails, sports facilities/fields) of London were at risk of flooding (Fig. 5.4). Two of the three water treatment plants within the modelled area were located on or next to the floodplain. Transportation infrastructure was also at risk. Numerous bridges cross the Thames River, including three rail crossings and 19 vehicle bridges.

Roadways at risk of flooding were primarily in the residential area to the north and west of the confluence (Forks of the Thames). In terms of emergency response and evacuation facilities, the City of London fared quite well under the flood hazard zone defined by the one wet climate change scenario. All 14 emergency services including fire, police, and ambulance stations were located outside the floodplain; although one fire station was located less than 250 m from the floodline. Of the eight hospitals within the study area, none were located within the floodplain, although three were located within 50 m of the 500-year floodline.

5.3.3.3 Adaptive Capacity Assessment

The natural hazard analysis developed a new hazard exposure under a "wet" climate change scenario but it did not assess the capabilities of the population exposed to the flooding hazard to respond or adapt. Adaptation, in this context, might include undertaking proactive flood-proofing actions prior to an event, responding during the flooding emergency, and recovering after a flooding event.

Vulnerability indices were developed to represent the attributes contributing to a lack of adaptive capacity and to map the distribution of coping/adaptation capabilities within the watershed. As part of the methodology, socioeconomic attributes for population and physical attributes of place were combined into three vulnerability indices representing ability to cope and respond, differential access to resources, and level of situational exposure (see Table 5.2). The variables were selected based on a review of literature assessing vulnerability to current hazards [6, 9, 14, 15, 24, 25, 46, 53, 57] and a changing climate [1, 2, 29, 66]. Statistics Canada 2001 Census data at the dissemination area (DA) level were used for the attributes. DAs are "small, relatively stable geographic unit[s] composed of one or more [neighboring] blocks" with a population of 400–700 people. They are the "smallest standard geographic areas for which census data are disseminated" [62]. Although hazards and vulnerability may occur at smaller geographic scales and at the household level, this scale of analysis is useful to and practical for local officials [9].

The method for calculating vulnerability indices was based on Wu et al. [66] and Chakraborty et al. [9], who modified the Cutter et al. [14] approach. In the case study, the three vulnerability themes—ability to cope and respond, differential access to resources, and level of situational exposure per DA—were mapped separately and aggregated into a total vulnerability score. Situational exposure—older pre-1970 neighborhoods built before implementation of floodplain restrictions—contributed greatest to total vulnerability. The DAs with a high proportion of older homes were clearly identified along the Forks of the Thames floodplain, concentrated at the Forks and along the two branches of the Thames leading to the Forks. This illustrates the key influence land use policy can have on vulnerability. "Differential access to resources" identified those DAs with a high proportion of low-income, renters, and single-parent families whose vulnerability may be higher because they typically do not have as many economic resources to devote to adaptation. Similarly, the "ability to cope and respond" indicator identified those DAs in

Table 5.2 Indicators selected for the Upper Thames vulnerability analysis: capacity to adapt to urban flooding [27]

Indicators	Rationale for contribution to vulnerability
Ability to cope and respond: *characteristics that affect ability to cope and respond to flooding*	
Over 65 years of age	Limited mobility (physical difficulties in evacuation); reluctant to leave homes; health-related problems, longer recovery
Under 19 years of age	Young children, in particular, physically weak; less mobile; legally dependent until age of 18
No knowledge of official languages	Language barrier; may not understand danger or respond appropriately; may not understand home preparedness measures
Females	Physically disadvantaged in evacuation or home preparedness; increased emotion, work, stress, physical domestic labor; slower to recover
Differential access to resources: *economic characteristics that affect access to resources in order to respond*	
Low-income households	Limited resources to prepare or respond (i.e., lack communication devices to stay informed, fewer social or community contacts; rely on public resources)
Single-parent families	Limited resources to prepare or respond
Rely on public transit	May lack mobility
Renters	Landlords lax on disaster preparedness or cleanup
	Limited resources and motivation to prepare or respond; less informed, fewer contacts
Level of situational exposure: *structural integrity of homes; likelihood of potential damage or failure*	
Housing type	Low structures (i.e., one- or two-story homes) are more susceptible to damage from flooding than apartments
Period of construction	Older homes may be constructed in floodplains; regulation not in effect until 1961 (high-water mark) and 1973 (regional storm level; i.e., 250-year floodline)
	Older neighborhoods have aging infrastructure, which may be more susceptible to flooding (e.g., water and sewer systems; dikes, dams)

the community whose populations are likely to have more challenges addressing pre-event vulnerability reduction, emergency response, and post-event recovery because of age, physical capabilities, language barriers, or time availability.

The map assessing total vulnerability is presented in Fig. 5.5. The standardized vulnerability scores are mapped in five classes: low (≤20th percentile), medium-low (21 to 40th percentile), medium (41 to 60th percentile), medium-high (61 to 80th percentile), and high (81 to 100th percentile). The DAs with high vulnerability and located within the 100-, 250-, or 500-year floodlines of the wet climate scenario are circled on the maps and indicate key vulnerable areas or "hot spots" within the Forks of the Thames study area. The analysis identified eight DAs with high vulnerability; one in the northern and eastern extent of the modeling window, and the remaining centered in the middle of the Forks of the Thames. These hotspots identify areas that warrant more detailed analysis (e.g., at the household level) in order

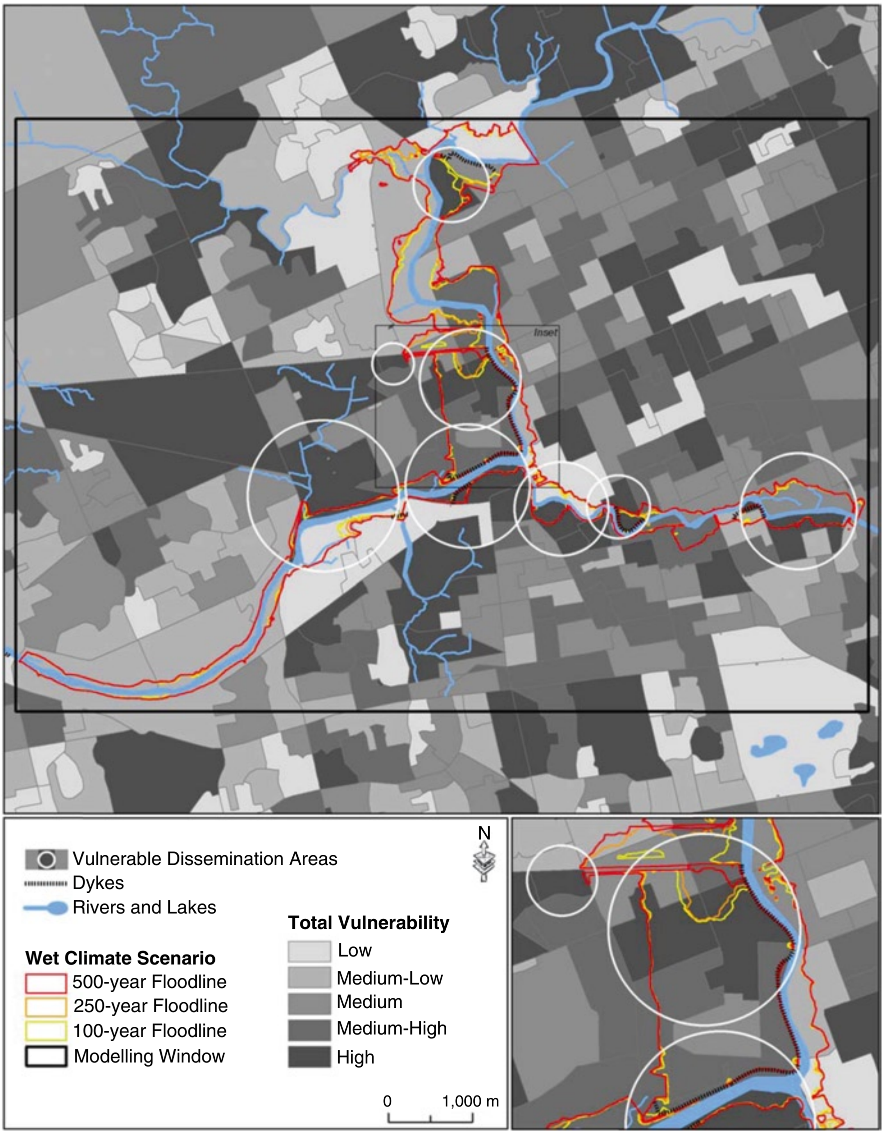

Fig. 5.5 Total vulnerability of the Forks of the Thames, estimated by combining ability to cope and respond, differential access to resources, and situational exposure attributes

to ascertain whether targeted programs might assist in implementing vulnerability reduction measures. For example, the DAs that include a high proportion of elderly or those relying on public transit might benefit from planning for community-assisted evacuation. Those DAs with a high proportion of low-income or single-parent families might require assistance (e.g., financial) to prepare for and cope with a flooding hazard. This vulnerability assessment approach tries to understand the human aspects of the issue; for example, those attributes of the DAs that might affect the capacity to adapt and where policy and programs could specifically address issues associated with the vulnerable populations.

5.3.3.4 Concluding Comments

Three approaches were used to explore vulnerability and the potential to inform adaptation. The hazards approach seeks to determine whether there is a change in the hazard and an increase in exposure to flooding because climate change is affecting precipitation. Here, the focus is on physical conditions and redefining the flooding hazard. Traditional metrics such as floodlines are redrawn and hazardous areas are expanded to accommodate the changing conditions. The assessment may also determine the number of people and buildings exposed and the potential economic cost of damages. The emergency management approach catalogs infrastructure—buildings, roads, bridges, emergency centers, and hospitals—exposed to flooding due to redrawn floodlines. This assessment helps understand the access, routing, performance, and safety issues that might arise with a flooding event. Indirectly, people are factored in. The adaptive capacity assessment approach integrates physical and human dimensions of vulnerability and offers insights into both. But the most important contribution is that it specifically considers socioeconomic attributes of groups. Adaptive capacity and vulnerability are integrated and this informs adaptation planning and decision making. Planners and decision makers are offered insights as to the types of policies that may facilitate adaptation and assist those who are most vulnerable.

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Chapter 6
Adaptation as a Decision Making Under Deep Uncertainty

A Unique Challenge for Policymakers?

N. Ranger

Abstract Climate change will fundamentally alter the nature of climate risks that we face as a society. The only viable approach to limit the impacts of climate change is to reduce global greenhouse gas emissions. But, due to the lags in the climate system, the world is already committed to further changes from historical emissions alone. The only way to reduce the impacts of this unavoidable climate change is through adaptation.

Adaptation brings with it both new and old challenges for decision makers. This chapter describes the major new challenge introduced by climate change as deep uncertainty about the future evolution of climate. This means that policymakers can no longer rely on traditional approaches for managing uncertainty. The past can no longer be assumed to be an adequate guide to the future. Not considering the true nature of the uncertainties in decision making today can lead to maladaptations, putting lives at risk, and wasting investments. Long-term investments and policies, like public infrastructure and sectoral planning, with long lead times and high sunk costs, have the highest potential for maladaptation. Not considering long-term climate risks from the outset in these decisions can lock-in future vulnerability and unnecessary costs.

This chapter suggests that, despite these challenges, in many cases, adaptation will be no more difficult than many other areas of public decision making. Many elements of adaptation plans, particularly in the near-term, are not necessarily highly sensitive to climate change uncertainties. Further, for long-term decisions, through employing a broad range of adaptation measures, considering flexibility up front,

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and sequencing measures to best cope with uncertainty, it is possible to build robust adaptation plans. By employing such principles in planning from the outset it is possible to reduce risk today and maintain flexibility to cope well with future climate changes.

6.1 Introduction

Climate change is one of the most significant challenges we face. Changes in climate will impact the environment, lives and livelihoods in many ways; including health, water supplies, food, ecosystems, and damages from extreme weather, such as flooding, droughts and storms [32]. The only viable approach to limit the long-term impacts of climate change is to reduce global greenhouse gas emissions. But, due to the lags in the climate system, the world is already committed to further changes from historical emissions alone. The only way to reduce the impacts of this unavoidable climate change is through adaptation.

Adaptation is defined by the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) as a series of adjustments, measures, or policies to reduce the vulnerability or enhance the resilience of a system to observed or expected climate change [1], reducing damages and maximizing potential opportunities. This will involve a diverse range of measures, from new crop varieties to sea walls, undertaken by individuals, organizations, and public bodies. Economic analyses have demonstrated that in many cases, well-planned adaptive measures can cost-effectively avert a large fraction of future losses due to unavoidable climate change over the next few decades [2, 9].

Some adaptation will be *reactive*, but the greatest benefits will come from reducing risks and seizing opportunities before the impacts occur (*anticipatory adaptation*). This will require planning and foresight about how climate will change. This chapter focuses on this planning process, and in particular, how one can make good adaptation decisions with the information available today. What is a *good* adaptation decision will depend on the objectives of the decision makers, but in many cases will be characterized as a decision that avoids exposure to potentially costly maladaptation, is informed and robust. The fact that there are information gaps is important. One of the main reasons that adaptation planning is difficult is that it is impossible to predict with certainty the future conditions that we need to adapt to. In many cases, this will mean that decision makers adopt strategies that keep options open, reduce potential regrets, and account for new information over time. An important conclusion of this chapter is that in many cases, adaptation will be no more challenging than many other areas of decision making. A key to simplifying adaptation is to consider the context of the problem holistically from the outset.

The following section considers what is unique about adaptation in the context of decision making and relates this to the broader challenges of climate change.

Section 6.3 explains why adaptation is a problem of decision making under *deep uncertainty*, as opposed to well-defined uncertainty (or *risk*, in the decision theory nomenclature), and introduces simple strategies designed to manage this uncertainty. Section 6.4 introduces a generic framework for adaptation decision making and Sect. 6.5 applies this, albeit at a high level, to flood risk management in the UK. Finally, Sect. 6.6 draws general lessons for adaptation planning. This chapter draws upon research developed at the Grantham Research Institute on Climate Change and the Environment and the Centre for Climate Change Economics and Policy (CCCEP), at the London School of Economics and Political Science, in particular, the recent report commissioned by the UK Adaptation Sub-Committee entitled, "Adaptation in the UK: a decision-making process" [33].

6.2 The Challenges of Adaptation for Decision Making

Climate change will fundamentally alter the pattern of weather risks. The industrial and policy areas most vulnerable to changes in climate are likely to be the same as those vulnerable to weather today, including agriculture, insurance, utilities, public health, the built environment and the natural environment [33]. The scale of impacts and their effects on local people, the environment, and economies will vary among regions. As global temperatures continue to rise, impacts will become increasingly negative and extensive across sectors and regions. At a global level, this could impact patterns of trade and commodity prices, migration, national security, and economic growth and development [38]. These types of global changes are difficult to predict, partly because the impacts of climate change will be heavily influenced by non-climate factors, including changing demographics and economic development, and the ability to adapt.

Lord Nicholas Stern described climate change as "the greatest market failure that the world has seen" [39]. At his speech to the UNFCCC Nairobi Dialogue [37] in late 2006 he identified four elements that together make climate change a unique challenge for decision makers. Climate change is:

- *Global*: manmade climate change is global in its source and its impacts and will require a global solution.
- *Long-term*: there are time lags of several decades between human actions now and their effects on the climate; the impacts of greenhouse gas emissions today will act over many decades to come and with increasing severity over time.
- *Uncertain*: the impacts of climate change, as well as the costs of action, are uncertain and these uncertainties increase significantly over time.
- *Potentially large and irreversible*: climate change has the potential to induce many large-scale and potentially irreversible impacts, such as irreversible losses of ecosystems and changes in many of the Earth's natural systems, leading to global-scale changes to patterns of trade, economic growth, and development.

Some of these challenges also apply to adaptation specifically, but others relate more to climate change in general and greenhouse gas mitigation, and so are less or partially applicable. For example, adaptation is:

- *Local*: While adaptation decision making may occur at a local, national, or even international scale, for the most part adaptation will be implemented at a more local scale and will usually aim to reduce the impacts of local changes in climate.[1]
- *Managing long-term risks but with immediate benefits of action*: Adaptation aims to reduce the level of weather-related risk due to unavoidable climatic changes over the near- and long-term. However, unlike greenhouse gas mitigation, adaptation has an immediate benefit in terms of reducing risk.
- *Uncertainty and lack of information*: Uncertainties in risk will increase over time. As the timescales of adaptation are generally limited to a few years or decades, the uncertainties associated with adaptation should be smaller. However, adaptation requires a higher level of resolution and detail about climatic changes expected (i.e., more information), thereby increasing the level of uncertainty.
- *Potentially large and irreversible*: as above, this is still relevant to adaptation, but in many cases will be less of problem for planning near-term adaptation.

In her speech to the NATO Science Workshop in June 2010 [29], Lynn Scarlett, former Deputy Secretary and Chief Operating Officer of the US Department of the Interior, highlighted a number of additional challenges of adaptation, which included:

- *Complexity of response*: Identifying the appropriate adaptive response will not always be straightforward. In many cases, managing climate change impacts through adaptation requires managing the complex web of interactions between human and natural systems. This is particularly the case for managing impacts linked with ecosystems, including biodiversity, crop productivity and water quality; even small human interventions can often cause unexpected outcomes. This introduces additional uncertainty.
- *Interactions with other challenges*: climate impacts can be difficult to disentangle from other stressors, such as demographic changes and environmental degradation; similarly, adaptation has synergies and tradeoffs with many other areas, such as resource management, conservation, land-use planning, and economic development. This means that adaptation requires a holistic approach.
- *Transboundary issues*: some impacts of climate change are transboundary (e.g., water supply) and will require transboundary actions and governance to manage them.

Some of these challenges are not unique to climate change and in addition to these, adaptation is likely to be exposed to challenges that are common across many other areas of risk management and decision making; including a lack of information, capacity, and skills; resource constraints; differing values, preferences, and objectives among stakeholders; short-termism; a lack of political will; and institutional barriers.

[1] Exceptions are where local adaptation aims to reduce the effects of global impacts of climate change; for example, building local resilience to global food price shocks.

A decision maker must consider these challenges as well as those that are unique to climate change when planning adaptation.

Given the extensive literature and experience available on these shared challenges, this chapter focuses primarily on overcoming those challenges that are more unique to adaptation; in particular, decision making under conditions of changing and deeply uncertain risk. Climate change means that decision makers involved in managing risk can no longer rely on history as an adequate guide to current and future levels of risk [23]. In mathematical terms, risk has become *statistically non-stationary.*[2] In addition, there is a greater need for risk management to be *anticipatory*; like greenhouse gas mitigation, delaying action increases the costs of climate impacts and the action itself, adaptation. Together these factors mean that, to be effective, risk assessment must shift from a backward-looking paradigm to one based upon forecasting current and future levels of risk. This paradigm shift exposes decisions to additional uncertainties and requires the introduction of new tools into day-to-day risk management.

6.3 A Climate of Deep Uncertainty

Projections of future climate change and its impacts are uncertain. Several authors have described the explosion of uncertainty along the chain of prediction from human emissions to economic impacts [26]. Uncertainty itself is not necessarily a problem; for example, engineers routinely make decisions about the design of infrastructure to cope with local weather conditions, which by their nature are chaotic and uncertain. These decisions rely upon known probabilities of different weather conditions (that is, *decision making under risk*, in the decision theory nomenclature). With climate change, the uncertainties are such that science is not yet able to provide a unique set of probabilities of different outcomes [35, 36] and this raises challenges for traditional decision making approaches. Recently, authors have begun to describe this situation as *deep uncertainty* [28].

6.3.1 Why Are Climate Change Projections So Deeply Uncertain?

The sources and types of uncertainty differ at each step of prediction and crucially, not all can be quantified with confidence [13, 35, 36]. Firstly, there is *aleatory* uncertainty, stemming from natural, unpredictable variations of the chaotic climate system. Aleatory uncertainties can be quantified but not reduced. More problematic is *epistemic* uncertainty, which stems from a lack of knowledge about the system,

[2] *Statistical non-stationarity* means that the statistical characteristics of a risk, such as a hurricane hitting the US Gulf Coast, are changing over time; for example, the average probability of landfall every season and its annual variability can no longer be assumed to be fixed with respect to time.

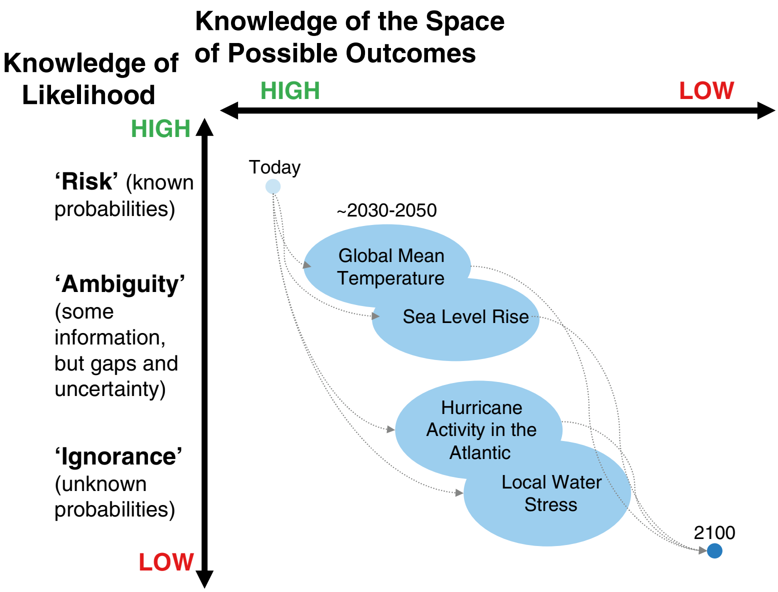

Fig. 6.1 Illustration of the evolution of uncertainty over time for different types of climate impact information. The vertical axis illustrates the level of knowledge about the likelihood of different outcomes. The horizontal axis illustrates the level of knowledge about the full range of possible outcomes. All impacts are assumed to start at a point of well-defined probability distributions for different outcomes (i.e., risk), but gradually evolve over time to a point where there are unknown probabilities of different outcomes (i.e., ignorance) and incomplete information about the range of possible outcomes. The small circles illustrate positions today and in 2100. The larger circles illustrate the positions in around 2030–2050. The exact positions on the chart are illustrative only

such as the response of regional climates to global greenhouse gas levels and the effects of warming on human and natural systems. Epistemic uncertainty can be reduced with more information. It is also theoretically possible to quantify epistemic uncertainties, but in the case of climate change this quantification is incomplete; some estimates are available [25] but all are conditional on the model approach and so retain unquantified residual uncertainties. Finally, the most problematic source of uncertainty comes from forecasting human systems and decisions, such as demographic changes, economic growth, land use changes and greenhouse gas emissions. Impact estimates are highly sensitive to these forecasts; without them it is impossible to predict the evolution of climate change impacts over time. The level of long-range foresight about human systems is limited and these uncertainties are largely irreducible [1, 28]. In the literature, these uncertainties are mainly treated through scenario-based approaches [31] with no attempt to attribute probabilities.

The level of uncertainty increases over time and varies by the type of impact being considered. This is demonstrated illustratively in Fig. 6.1. The vertical axis in Fig. 6.1 represents the level of uncertainty and the horizontal axis, the level of knowledge about the range of possible future climates. The positions of points and circles represent the level of information with respect to these two dimensions for different prediction lead times (today, 2030–2050, and 2100) and types of impact.

In the short term (roughly the next 1–10 years), the influence of epistemic and human elements of uncertainty are generally relatively small. This means that uncertainty is dominated by aleatory factors, which can be quantified. The level of information today might therefore be characterized as high knowledge of likelihood (*decision making under risk*) and high knowledge of possible futures (i.e., the top left corner of Fig. 6.1).

In the longer term, epistemic and human elements of uncertainty become more important, moving decision making into a paradigm of deep uncertainty (either *ambiguity* or *ignorance*). However, the evolution of uncertainty over time varies depending on the type and spatial scale of impact. In general, the lowest uncertainties are associated with large-scale mean changes in the physical environment, such as global mean temperature. However, projections that rely on less well understood physical processes (introducing greater epistemic uncertainty), like global sea level rise, are more uncertain. Similarly, climatic changes that rely upon modeling local-scale changes, such as precipitation and weather extremes in general (including storms, flooding and droughts), have a higher uncertainty as impacts require high-resolution modeling, which is currently constrained by computational requirements. Impacts on local human and natural systems are most difficult to predict as they introduce both epistemic uncertainty in linking climate conditions with impacts (e.g., the effects of drought on water supply) and human elements (e.g., interactions of water supply with population growth). At longer prediction lead times it becomes more difficult to predict even the range of possible impacts (the horizontal axis on Fig. 6.1). For example, towards the end of the century, it becomes more likely that some hitherto unknown process, a *big surprise,*[3] would change our anticipation of the range of impacts.

Continued research to better constrain projections is important. However, for adaptation planning, it is important to understand that this research is unlikely to yield significant reductions in overall uncertainties on the timescales that many adaptation decisions need to be made. For example, a number of authors highlighted that the level of certainty is limited by fundamental irreducible uncertainties in projections [13]. In addition, the evolution of climate models has shown that improved knowledge does not necessarily imply narrower projections; in the past, new research has tended to highlight previously missing processes (such as the dynamics of ice sheets or carbon cycle feedbacks) that have increased the quantified uncertainty range [23]. Adaptation planners can therefore benefit from focusing on approaches to make decisions with the information available today. For these reasons, there is a need to employ decision making approaches that take account of the full scope of uncertainties.

[3] A 'big surprise' might be, for example, a natural process analogous to carbon feedbacks or dynamic instability of ice sheets (which were until recently unforeseen but are now known to have a potentially significant influence on future impacts), or a human process, such as technological innovation or unforeseen economic developments.

6.3.2 The Impact of Uncertainty on Decision Making

Given the relatively well-defined nature of near-term climate, for more short-lived adaptation measures, like changing crop varieties in agriculture, decisions will be made under conditions of *risk,* or well defined probabilities, where the dominant driver is aleatory uncertainty. This will likely be little different from risk management decision making today and may be subject to some of the same challenges.

In the case of long-lived adaptations, like public infrastructure, decisions will be more sensitive to the more uncertain long-term climatic changes and therefore, decision making is likely to be under conditions of deep uncertainty, either:

- *Ambiguity*: incomplete information about the likelihood of different outcomes or multiple conflicting estimates; or
- *Ignorance*: no information about the likelihood of different outcomes.

Hall [22] and Dessai et al. [13] warn that improper consideration of the true level of uncertainty in projections (e.g., residual uncertainties in probabilistic climate projections) could lead to unnecessary costs.

Figure 6.2 can be used to illustrate the effect of ambiguous probability estimates on a decision. It takes the hypothetical case of a town that has recently been damaged by flooding and where a decision must now be made over how to rebuild the infrastructure. Given that infrastructure is built to last around 50–100 years, decisions are potentially sensitive to climate change. To simplify the example it is assumed that a decision must be made today among five defined options, from repairing the existing infrastructure to a major re-engineering including resilience measures and some retreat from the high-hazard areas. It is assumed that the decision maker has already appraised the costs and benefits of different options and knows over what range of potential changes in flood risk each option would be the most desirable; this is shown by the shaded regions in Fig. 6.2. For simplicity, the example only considers one future time interval (representing 2050) and assumes that flood risk is directly linked with the wettest day precipitation (the x-axis in Fig. 6.2).

Assume that the decision maker is given one probability distribution of wettest day precipitation; the solid bell-curve in Fig. 6.2. This projection suggests a 90% confidence interval that wettest day precipitation will change by around −15% to +30% from current levels, with a best guess of around a 5–10% increase. If the level of confidence in this probability distribution were high (and risk aversion low), then the decision maker might resolve to select Option 2, upgrading the existing infrastructure.

However, projections of extreme precipitation at a local level are ambiguous. Climate models do not yet fully represent all the processes involved in generating localized precipitation extremes and this means that probability distributions have residual uncertainties. To illustrate the effect of such ambiguity, imagine that the decision maker receives a new probability distribution in 5 years time that, following some advance in regional climate modeling, now has a far higher degree of confidence. It gives a new estimate of future changes, with a best guess of around a 20% increase in wettest day precipitation and a range of −5% to +60% (the black

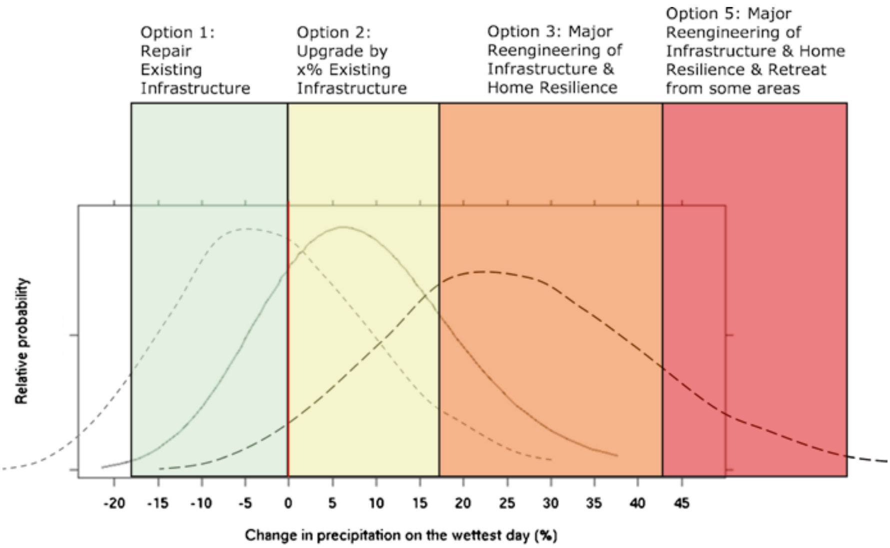

Fig. 6.2 Illustration of the effect of deep uncertainty on decision making for a public infrastructure decision related to flood risk management. The case is a recently flooded town that is about to undergo repair to its public infrastructure. The decision maker faces the challenge of deciding how to repair the infrastructure given several probability distributions of future extreme precipitation, some projecting a small decrease in wettest day precipitation and others projecting an increase. The shading represents the range of values over which the decision maker would select different adaptation options, from no adaptation (simply repairing existing infrastructure) to strong adaptation (major re-engineering of infrastructure, resilience buildings and retreat from some areas). The example is purely illustrative

dashed bell-curve in Fig. 6.2). In this case, merely upgrading the existing infrastructure would have left the town under-adapted to climate change. The decision maker would then need to either incur additional costs from replacing the 5-year-old infrastructure before the end of its useful life, or take no action and risk additional damages to the town. These are two examples of maladaptation. Conversely, if the new distribution showed a potential decrease in wettest day precipitation, for example the grey dashed bell-curve in Fig. 6.2, then the decision maker should have only repaired the existing infrastructure and so the town incurred unnecessary costs from upgrading the infrastructure.

6.3.3 Planning to Avoid Maladaptation

Maladaptation can be defined as inadequate or faulty adaptation; a process that leaves a system less well adapted to climate change than is desirable. Maladaptations include:

- *Inaction*: for example, a failure to adjust water resources management to account for climate changes.

- *Over-adaptation*: where adjustments are made that are proven to be unnecessary given the climate realized; e.g., a sea defense built to withstand 4 m of sea level rise that never emerges.
- *Under-adaptation*: where adjustments are *not enough*; they do not achieve the desirable reduction in losses for the realized climate.
- *Faulty adaptation*: where adjustments are made, but are later found to be either not adaptive or counter adaptive, actually increasing impacts above what they could have been given improved ex-ante adaptation. For example, a policy instrument that aims to incentivize adaptation but is either ineffective or counterproductive.

Maladaptation is particularly a risk (i.e.*, both more probable and more potentially costly*) for decisions that are high stakes, long-lived and irreversible; for example, those involving long-lived infrastructure and buildings, regulation and sector-level planning [19]. Adaptation planning should therefore seek to avoid a situation in which a system is more maladapted to the climate than is desirable and as a result, incur additional costs or fail to seize climate-related opportunities.

The ambiguity in projections means that a decision maker cannot estimate with certainty how decisions should be made today to maximize future productivity or minimize costs. For example, it is not possible to predict exactly how high a sea wall should be to maximize net benefits over the next 50 years.

There are two approaches to cope with this. The first involves optimizing a strategy based on the best available probabilities of different outcomes to maximize expected utility; hereafter, *optimizing returns* (as illustrated in the example above). The second involves making a strategy that is robust to the deep uncertainty in projections; that is, is beneficial under any future scenario. Both strategies involve tradeoffs. The first strategy is exposed to risk of maladaptation and this risk will increase with the level of ambiguity in projections. For the second strategy, there tends to be some additional upfront cost or productivity tradeoff associated with robustness.[4] In reality, the choice is not which of these two strategies to adopt, but what is the best level of tradeoff along a continuous scale between optimizing returns and robustness [27]. Several decision tools are available to enable one to determine where a strategy should sit along this scale; in general, the lower the level of confidence in projections and the greater the sensitivity of decisions to those projections, the greater the benefit of robustness-based approaches.

As a general rule, robust decision making means avoiding decisions that will inhibit future flexibility to cope with climate change; i.e., avoiding inflexible decisions. An example of an inflexible adaptation option is one that will only perform under a relatively narrow range of future climates; for example building new homes

[4] Robustness is defined here as an adaptation option's ability to perform adequately across a wide variety of possible futures.

on a high-risk flood plain or investing in a reservoir that can only cope with current climate conditions. Decisions that are vulnerable to inflexibility are typically long-lived decisions with high sunk costs.[5] In many cases, such decisions will mainly be found in public sector decision making, but could arise for private actors involved in building hard infrastructure, such as energy and water companies.

In many cases, even where dealing with long-lived decisions with high-sunk costs, flexible options are available and can be shown to be desirable [19]:

- *Using measures that are suitable over the full range of plausible futures.* For example, an early warning system for flooding or an adaptation measure that is designed from the outset to cope with a range of climates; such as a new house with a cooling system that operates effectively over the full range of future maximum summer temperatures predicted by models today. These types of designs can be more costly, less effective,[6] and may be infeasible [23].
- *Building flexibility*[7] *into the adaptation measure from the start*. Build in the option to adjust a measure if required, for example, building a flood wall or reservoir with larger foundations so that it can be heightened if necessary rather than replaced. In some cases, such measures will increase costs.
- *Building flexibility into the adaptation strategy itself over time*. For example, sequencing adaptation strategies so that no-regrets options are taken earlier and more inflexible measures are delayed in anticipation of better information. However, delay can lead to greater costs; for example, delaying the building of a much-needed major reservoir could leave a water resource zone more vulnerable to climate-related shocks [3].

The following section describes a process to ensure a decision maker to identify and appraise adaptation options with the aim of designing robust adaptation strategies.

6.4 A Framework for Adaptation Planning and Decision Making

The complexities involved in adaptation (Sect. 6.2) point towards the need for a structured approach to adaptation planning, where uncertainties can be dealt with in an analytical framework that makes assumptions explicit. A well-structured process

[5] *Sunk costs* are past costs that cannot be recovered, making decisions effectively irreversible. Most public infrastructure involves costs that cannot be recovered.

[6] For example, a health-care system that invests in measures to account for a range of possible future climate-related diseases across all plausible futures may be less well equipped to deal with any one individually.

[7] Flexibility is defined as an adaptation's ability to be adjusted to new information or circumstances in the future.

Fig. 6.3 A framework for adaptation decision making [33]

will allow decision makers to assess the priority of measures against other projects, to weigh the benefits and tradeoffs and inform their sequencing over time. Figure 6.3 proposes such an approach. This framework is designed to be applicable to a wide range of adaptation questions, from focused adaptation projects to policymaking and national adaptation plans.

The framework is not dissimilar to other more generic frameworks for decision making, but with some refinements for adaptation. The framework is in the spirit of a number of other adaptation planning processes; in particular, a risk management approach, as advocated in [41, 42]; the policy-first approach described in Dessai et al. [14, 15]; and the recent supplementary guidance to the HM Treasury Green Book on accounting for climate change in project appraisal [24, 40].

The proposed framework is divided into three stages: "Structure the Problem," "Appraise Solutions," and "Implementation." However, adaptation is not a one-off, but an iterative process involving planning, implementation, and review (in Fig. 6.3 this is indicated by the grey arrow that joins Step 5 back to Step 1). This chapter focuses on the planning components: structuring the problem and then appraising solutions:

- *Structuring the problem* can be thought of as context setting or risk screening; it enables a decision maker to understand the nature of the problem, including the current vulnerability to weather, the relative importance of climate change and other drivers of risk, the appropriate adaptation options; and the objectives and constraints of the case. Importantly, structuring the problem involves understanding the interplay among these factors. For example, the analysis may reveal that all adaptation options are short-lived and so insensitive to climate change uncertainties (e.g., some agricultural adaptation); it may show that non-climate factors, such as increases in water consumption, are the dominant driver of risk; or it may reveal that regulatory constraints limit the range of appropriate adaptation options (e.g., in the UK, extraction of water from rivers is limited to protect ecosystems). As these examples illustrate, structuring the problem can often narrow and simplify the decision analysis. The information needed for this step is high-level but can have significant value in improving the efficiency of the appraisal.
- *Appraising solutions* involves more specific qualitative and quantitative assessment to help a decision maker choose among different options based on the factors identified in the first stage, and consider the sequencing of options over time. This stage need not occur in all cases, or could be conducted at a back-of-envelope or qualitative level rather than a detailed quantitative level. For example, if *structuring the problem* identified clear solutions then additional analyses may not be required. This might be the case where the decision maker is working with a well-defined single objective, the number of options is small and options are no-regrets. Detailed quantitative analysis will typically only be required where the choice among options is more subtle, more sensitive to assumptions (including climate change uncertainties), and where there are significant potential tradeoffs to be assessed among different objectives and decision criteria. These analyses might involve decision methods, such as expected value analyses, real-options analyses, or robust decision making. These types of decisions are more common to the public- or large private- (e.g., water and utilities companies) sector organizations involved in planning long-lived infrastructure projects with high sunk costs, or long-term sector-level planning and regulation.

These first two stages are illustrated in the following section with an application to UK flood risk management.

This section focuses on the key principles of the framework in terms of managing deep uncertainty in adaptation; a fuller description that considers the broader adaptation challenges can be found in Ranger et al. [33].

6.4.1 A Systems Approach Founded on Understanding Current Vulnerability

The highest value information in an adaptation decision is likely to come through understanding the current vulnerability of the system. This forms an important part of structuring the problem and an input to appraising solutions. Unless there is a good understanding of the current vulnerability of the system to weather and other risk drivers, it is impossible to fully assess how it will be affected in the future.

Understanding current vulnerability allows one to identify the adaptive capacity of the system, future susceptibilities to changing weather patterns and also to identify no-regrets adaptation options. It requires a systems approach; for example, identifying if and how the system has been affected by weather in the past and mapping the pathways through which climate and other stressors can affect the system, including any thresholds in the system that may lead to a significant increase in impact (for example, design risk-standards for existing public infrastructure). Future climate change will scale up or down current stressors. A systems approach also allows one to identify adaptation measures with a material effect on reducing vulnerability.

6.4.2 Context First, Not Science First

Many early risk assessment exercises tended to begin by using climate models to generate scenarios that could then be analyzed with impacts models. These are generally known as *science-first* approaches. This is different to the *context-first*[8] approach advocated in this chapter, where the decision maker is encouraged to form a comprehensive understanding of the nature of the problem before employing detailed, science-based projections in the *appraising solutions* stage.

An argument against the science-first approach is that it is much more exposed to ballooning of uncertainties [8], meaning that the appraisal of options can become impracticable [15, 41]. A context-first approach is also more efficient, in that it identifies high-value information at the start and so streamlines the analysis.

Some science-based projections are included in structuring the problem, but this information need only be high-level; future projections should not be treated as exact at this stage and significant time should not be spent on generating quantitative future scenarios. The focus should be on the sensitivity of the system itself over time to all risk drivers. In some cases, detailed projections may not be needed at all. For example, if a clear solution is identified through structuring the problem, then additional analyses are unnecessary, or could be at a generic quantitative level.

[8] Also known as the *policy-first*, *bottom-up,* or *assess risk of policy* approach (e.g., [15]).

6.4.3 Identify No-Regrets Measures

Setting the context and building an understanding of current vulnerability is particularly important in identifying *no-regrets* versus other measures. No-regrets measures are defined as those that provide benefits under any climate scenario.[9] No-regrets measures, as well as flexible options, may form an important part of a robust adaptation strategy. Ranger et al. [33] discusses four types of no-regrets measures:

- *Measures associated with managing current climate variability*, such as providing risk information and monitoring, insurance systems, research and development, or conserving existing high-value ecosystems.
- *Measures associated with managing non-climate-related drivers of risk*, such as reducing leakage in water systems, enhanced planning and building regulation controls, building natural drainage systems in urban areas, rebuilding soil fertility, and water quality management.
- *Short-lived adaptations* (i.e., those with a lifetime shorter than the timescale on which climate change is expected to affect decisions—perhaps 5–10 years in most cases), such as changing crop varieties in agriculture.
- *Broader measures aimed at reducing vulnerability and building resilience to shocks and general stresses*, such as early warning systems and emergency response for flooding, building water transfer networks between regions, and capacity building (skills, knowledge, and information).

All of these options will be no-regrets as long as they are implemented in a way that does not limit flexibility to cope with future climate change. Many can have immediate and significant benefits, as well as increasing flexibility to cope with longer-term risks.

6.4.4 Employ Decision Methods That Take Full Account of the Scale of Uncertainty

In appraising solutions, decision methods can be used to help a decision maker to distinguish and prioritize options in cases where this choice is more subtle and sensitive to assumptions. For example, they can help to rank options with different costs, tradeoffs, and benefits against a set of criteria, or appraise the option of paying more now to incorporate extra flexibility (such as a reservoir of greater volume) to account for future climate change uncertainty. Decision methods can be a powerful tool because they provide a formalized and transparent structure. They take as inputs

[9] This is a narrower definition of no-regrets than is used in some previous studies and does not imply 'no-regrets' in terms of zero costs or zero tradeoffs with other investments.

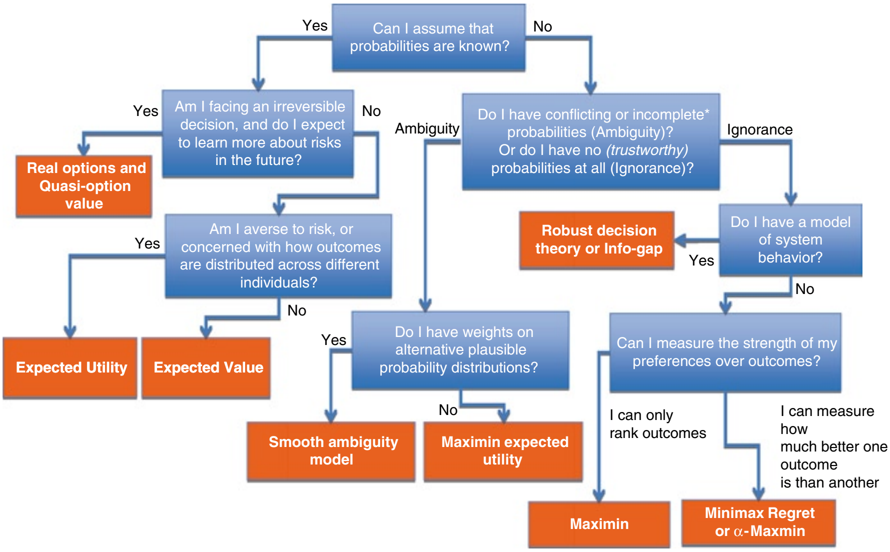

Fig. 6.4 Simplified flow diagram illustrating the linkages between decision methods and characteristics of information and decision criteria [33]

information on the objectives and characteristics of different options and provide a ranking of those options on that basis. These types of analyses can be resource intensive, but can be worthwhile particularly where the stakes are high, for example, in the case of many large-scale infrastructure decisions.

A range of decision methods are available and each is appropriate in slightly different circumstances; this is illustrated in Fig. 6.4. For example, if the probabilities of different future climate projections are known and not expected to change with new information then the decision analysis might be best suited to an expected utility analysis or expected value analysis. Expected value approaches are used frequently in, for example, flood risk management assessment [11], where the probabilities of flooding are assumed to be known based on modeling and historical data. Conversely, if there is a trustworthy set of probabilities based on current knowledge but these are expected to be refined over time with new information, then a real-options analysis would be more appropriate; this can evaluate the benefits of acquiring more information before acting. Finally, if there are no trustworthy probability estimates, then robust decision theory may be more appropriate.

Figure 6.4 demonstrates that the level of confidence in projections is an important factor in selecting a decision method. Decision methods that reflect the true extent of the uncertainty about the future and rigorously account for attitudes towards this uncertainty are important tools for designing successful strategies. For long-lived decisions, more exposed to climate change uncertainties, methods such as robustness-based approaches and real-options analyses are likely to be important. An example application of a real-options analysis is given in the following section.

6.5 Application to UK Flood Risk Management

This section applies the framework proposed in the previous section to the problem of flood risk management under climate change in the UK. The first part of this section will apply the *structuring the problem* component of the framework to map the context of adaptation across the sector and draw high-level implications for adaptation decision making and options appraisal. The second part of this section will draw on the Environment Agency's Thames Estuary 2100 project as an example of a complete appraisal of options under deep uncertainty. A number of the lessons drawn from this analysis will also be applicable to other forms of public sector decision making, as well as adaptation for long-term infrastructure investments in general. These will be summarized in Sect. 6.6.

6.5.1 The Context of UK Flood Protection Under Climate Change

Flood risk management in the UK is an interesting case as it involves high levels of current exposure, highly uncertain changes in risk due to both climate and non-climate drivers, and many long-lived hard-infrastructure investments with high sunk costs. This makes decision making in this sector high-stakes and potentially sensitive to climate change; the potential for costly maladaptation is high.

In the UK, the government plays a central role in planning and implementing flood protection and is expected to spend roughly £800 million on coastal and river flood protection in 2010–2011. Climate change is already recognized as a driver of increasing flood risk and is taken into account (albeit simply[10]) in public-sector project appraisal. As an illustration of an application of Fig. 6.3, this section reviews the broad context of flood risk management in the UK, from a policy perspective, and draws high-level conclusions for adaptation planning that might inform a more detailed appraisal of specific policy solutions.

Objectives and constraints: While there are no stated public-sector adaptation-specific objectives in flood protection, arguably climate change is intrinsic within the broader objectives of public investments. The goal of public investments in flood protection is to maximize the overall benefit of public resources within budgetary constraints [11]. This is defined in terms of a number of *decision factors*, both eco-

[10] Defra guidance calls for a "consistent and risk-neutral approach to considering climate change impacts" and emphasizes the use of managed adaptive approaches based on no-regrets actions where possible to maintain flexibility. A precautionary approach, consistent with a level of acceptable risk, is discussed where flexibility is not possible. Defra 2006 supplementary note on climate change defines time-evolving climate change allowances and sensitivity ranges to be used in project appraisal to ensure consistency and comparability [10].

nomic and non-monetary. For example, there is a target that, in general, flood risk management investments should provide at least £5 return on every £1 spent. Project appraisal guidance also set out a number of guiding principles beyond cost-effectiveness, in particular related to distributional issues and social justice. For example, national targets are set related to reductions in properties at risk, and specifically deprived households, and protection of ecosystems and sites of special interest. There are also other regulatory constraints that affect decision making, related to—for example—the protection of certain historical sites and ecosystems and prohibiting tradeoffs with water quality.

Current vulnerability: The UK has a relatively high exposure to flooding. The Environment Agency's recent *National Flood Risk Assessment* estimates a total of 5.2 million properties (1 in 6) at risk from flooding in England alone [16]. Of the 2.4 million of these properties exposed to flooding from rivers and the sea, just less than a quarter of these are exposed to significant risk, defined as greater than a 1 in 75 (1.3%) chance of flooding each year. The remaining 2.8 million properties are susceptible to surface water flooding associated with heavy rainfall. This source of flooding is more uncertain, but was the dominant source of the large-scale flooding of summer 2007 [7].

Many of the exposed properties are protected to some extent, but the residual risks are significant: today, the expected annual damage to property across the UK is estimated at more than £1 billion. Damage from localized flooding occurs relatively frequently in the UK. Less frequently, the UK experiences major flooding that affects large areas and many thousands of people simultaneously. The most recent and severe was the 2007 summer floods when 55,000 properties were flooded and 13 people were killed [7]. As well as the immediate risk to life and damage to property, flooding causes a range of longer-lasting impacts, including stress, injury, displaced persons and disruption to economic activity and public services. Important and critical infrastructure, such as energy, water, transport and communications infrastructure, and public services are also vulnerable to flooding. After the floods in 2007, half a million people were left without water mains or electricity [7].

The region with the highest total number of properties at risk is greater London (almost 1.1 million properties), but most of these are at low risk and protected by defenses. At higher risk are the Yorkshire and Humber region, the South East, the East Midlands, the North West, and the South West, which each have more than 200,000 properties at moderate-to-significant risk. Many rural villages, properties and agricultural lands are at significant risk from flooding and will typically not be protected to as high standards as urban areas, if at all. The east coast of the UK is most susceptible to coastal flood risk, being exposed to storm surges in the North Sea. London is exposed to storm surge risk but is currently protected by a system of defenses, including the Thames Barrier.

There is no firm evidence that climate change is already impacting flood frequency in the UK. Today, the effects of natural variability in climate and non-climate drivers, such as land-use change and development, have a much greater influence on flood risk [34].

Future sensitivities: In the future, the UK Climate Projections 2009 (UKCP09) predict wetter winters for most of the UK, along with drier summers, particularly in the South East [25]. The link between these changes and flood risk is nontrivial and will depend on many local factors. There is also much ambiguity over future localized precipitation changes, particularly for the extreme events normally linked with flooding. In general, more flooding might be expected during winter as a result of higher and more extreme precipitation. During summer there may be less frequent, but more intense, flooding. Increases in sea level will also mean an increase in coastal flood risk; this effect is much more visible even today. The effects of potential changes in storm surge frequency on coastal flood risk are less well understood; the most recent estimates from UKCP09 suggest that changes could be small, but have significant uncertainties [30].

A handful of studies have provided quantitative estimates of the effects of climate change on flood risk. For example, in its long-term investment strategy, the EA estimates that under a mid-range climate change scenario (not including other risk drivers), around 60% more properties could be at significant risk of flooding by 2035 [17]. Recent research by the ABI [6] suggests that a global warming of 2°C (expected to occur in the middle or second-half of the twentieth century) could lead to an 8% increase in average annual insured losses from river and surface water flooding and an 18% increase in 1 in 100 year losses (to around £5 billion). Earlier research by the ABI suggested that with only 40 cm increase in mean sea levels, damages from a 200–250 year return-period storm surge would increase from £7.5 billion to £16 billion if defenses were not improved [5].

Non-climate drivers of risk are likely to remain important. Changes in land-use and development significantly affect the likelihood and damage from flooding and are likely to be the most important drivers of trends in risk, at least in the near-term, and have a lower uncertainty than climate change[11] [7, 20]. For example, ABI [4] estimates that the costs of a 1 in 100 year flood event across Thames Gateway could almost double as a result of the new developments. In coastal regions, exposure to sea level rise can be aggravated by subsidence (for the South and East UK) and coastal erosion (particularly problematic in areas of the East Coast UK). Coastal erosion can itself be accelerated by sea level rise and increased storminess. The increase in risk due to the natural aging and deterioration of current flood protection can also drive increasing risks.

Adaptation options and characteristics: There are a broad range of adaptation options for flood risk management, many of which can be complementary (as opposed to substitutions) and beneficial as part of an integrated strategy:

- *Risk information and early warning*: flood risk assessment and mapping to understand who is at risk and inform adaptation strategies; and early warning systems to forecast flooding then warn those at risk as well as responders.

[11] For example, urbanization can reduce natural drainage (increasing runoff and reducing filtration), increasing the risk of surface water flooding.

- *Preparedness and response*: disaster preparedness and ex-post actions can reduce the fatalities and indirect impacts of flooding; this may include emergency services; evacuation and rescue; temporary protective measures for properties and critical infrastructure; and facilities for provision of shelter, food, and water. Strategies and support for cleanup and recovery can reduce disruption and distress.
- *Development and land-use planning*: Land management and development controls can reduce flood hazard (i.e., the frequency and intensity of flooding), for example by avoiding the removal of vegetation; and flood exposure, for example by managing new developments out of high-hazard areas.
- *Hard infrastructure*: Constructing, upgrading, and maintaining flood defenses, pumps, and flood storage to reduce flood hazard.
- *Soft infrastructure*: utilizing the natural environment to help reduce flood hazards [43]. These measures can work alongside hard infrastructure or—in some cases—replace it. Measures operate through slowing the flow of water, reducing peak river flows and surface runoff. They include enhanced water retention (by enhancing soil conditions), provision of storage (on-farm reservoirs, enhanced wetlands, and washlands), and slowing flows (restoring smaller water courses, managing agricultural lands, and planting cover crops). Measures can also be applied in urban areas, such as green roofs to intercept water, permeable paving, surface water attenuation pools, and green flood corridors along rivers.
- *Managed retreat*: reducing exposure by retreating from areas where flood protection is no longer suitable (usually involving moving the line of defenses or removing defenses).
- *Property-level adaptation*: Property-level flood resistance and resilience measures, such as door guards and dry flood proofing, to reduce vulnerability to flooding. This can also include purchasing insurance to cover residual property and casualty risks.

Table 6.1 summarizes the key characteristics of these adaptation options that have implications for their role in managing risk and uncertainty. Not of all these options would be implemented by the public sector, but they are included as planning adaptation requires a holistic view of all options and the public sector could play a role in their adoption through incentives, regulation, and the provision of information [12].

Implications for Decision making: The ambiguities in estimates of future flood risk and high potential sensitivities make adaptation planning in this sector a process of decision making under deep uncertainty. As described in the previous section, the first stage of adaptation planning is structuring the problem; an important outcome of this is an understanding the flexibility of different adaptation options to cope with climate change uncertainties and their roles in managing the different elements of risk. From Table 6.1, it is possible to categorize the measures in these terms; this is illustrated in Table 6.2.

Tables 6.1 and 6.2 show that there are many no-regrets options available that can have significant benefits in terms of reducing risk under any climate scenario,

Table 6.1 Characteristics of flood management adaptation options [33]

Adaptation option	Summary characteristics	Geographical constraints	Relative economic costs	Relative economic benefits	Common co-benefits	Common trade-offs	Lifetime (lead-time, turnover)	Flexibility & sunk-costs	Distribution of costs and benefits	Risks
Hard barriers and other infrastructure (including flood wall, embankment, hard flood storage)	Anticipatory; complement		High (~£0.5–4 m per km embankments and sea walls)	Potentially high		Potential damage to ecosystems and visual appearance; downstream risks	Long (20–100 years); long lead-time for large projects	High sunk-costs but can incorporate flexibility	Typically taxpayer funded, local benefits	Small risk of failure; larger if not maintained
Enhanced 'hard' drainage and sewerage systems	Anticipatory; complement	Typically urban	High if early capital replacement; low if in line with turnover	Potentially high			Long (100 years)	High sunk-costs, can incorporate flexibility	Typically taxpayer funded, local benefits	Risk of failure if not maintained
Managed realignment/ retreat	Anticipatory; typically substitute	Typically coasts and more rural areas	Medium to High (e.g. £1 – 40 m with environmental restoration)	Potentially high	Restoration of natural habitats and ecosystems	Possibly sacrificing some land or property			Typically taxpayer funded, local benefits	
Risk-averse planning of new developments	Anticipatory; complement	Relevant in flood exposed regions	Low *(but potential high costs if build in exposed regions)*	Potentially high		Potential trade-offs with development objectives	Long		Policy	None *(but risk if build in exposed regions)*
Large-scale 'Soft' Infrastructure (natural barriers, natural flood storage, enhanced soil conditions)	Anticipatory; typically complement	Requires large land areas for natural ecosystems	Medium (£10 – 100 k small-scale wetland and channel restoration; £1 – 10 million major channel restoration, flood storage, floodplain reconnection)	Medium (uncertain, potentially high local benefits)	Ecosystems and associated benefits	Other land uses; downstream risks	Medium	Lower sunk-costs	Local benefits; range of possible funders (e.g. local community, charities)	Potentially higher risk of failure and more uncertain benefits than hard infrastructure

(continued)

Table 6.1 (continued)

Adaptation option	Summary characteristics	Geographical constraints	Relative economic costs	Relative economic benefits	Common co-benefits	Common trade-offs	Lifetime (lead-time, turnover)	Flexibility & sunk-costs	Distribution of costs and benefits	Risks
Urban 'soft' infrastructure (green roofs and permeable pavements)	Anticipatory; typically complement	Typically urban	Medium (Green roofs – additional £10–20 per sqft; surface solutions ~£100 – 200 k per small-scale project)	Uncertain	Ecosystems; cooling and insulation of urban areas and buildings		Medium	Lower sunk-costs	Local benefits; range of possible funders (e.g. local community, charities)	Potentially higher risk of failure and more uncertain benefits than hard infrastructure
Property-level resistance and resilience measures (retrofit or new build; voluntary or implemented through building regulations)	Anticipatory; typically complement	More feasible for new build or during refurbish-ment	Low-High £100–£40,000 (retrofit, depending on scale, e.g. >£20,000 structural changes e.g. foundations; cheaper for new build)	Typically payback after one event. E.g. Resistance measures are cost-effective for properties with annual chance of flooding >2%.			Long	Low to High sunk-costs; potential for flexibility	Individual benefits	Low risk if well maintained; more uncertain benefits
Temporary barriers (including demountable defences and sand bags)	Reactive; typically complement	Limited suitability	Low-Medium; labour intensive	Low to Medium; ok for some shocks but not economic if permanent			Temporary	Low sunk-costs and flexible	Individual benefits; usually community or individual	High risk of failure
Temporary property-level measures (e.g. flood boards, air-brick covers)	Reactive; typically complement		Low (e.g. <£100 airbrick covers; 1,000+ for boards etc.)	Medium			Temporary	Low sunk-costs and flexible	Individual	High; but lower risk of failure than sandbags

Disaster response planning (e.g. evacuation procedures and emergency services)	Anticipatory; typically complement	High	Components can benefits all disasters	Taxpayer funded; all benefit	Some risk of failure
Risk information and early warning systems	Anticipatory; typically complement	High		Taxpayer funded; all benefit	Some risk of failure

Table 6.2 Categories of adaptation measures

Categories		Options
Reactive measures (i.e., post-flooding)		Disaster response: emergency services
Potential no-regrets (beneficial under any climate change scenario) (each also reduces vulnerability and increases resilience to shocks)	Managing current climate variability	Risk information and monitoring Early warning systems Preparedness and response Insurance
	Managing other risk drivers	Risk-averse planning of new developments (including the design of location and drainage) Natural drainage systems: urban and rural areas Managing risks related to coastal erosion and subsidence
Measures with co-benefits		Large-scale natural soft infrastructure projects
Potential for flexibility		Property-level resilience (and some resistance) Some types of hard infrastructure Upgrading old drainage and sewerage systems
Inflexible options (long-lifetimes and lead times, irreversible, potential for high-regrets)		Some types of hard infrastructure High-spec property-level resistance measures Managed retreat

including effective ex-post flood response, early warning systems, insurance, and effective development planning. The mapping of current vulnerability and future sensitivities demonstrated that non-climate drivers, in particular land-use change (e.g., new development and urbanization), as well as current climate variability, are likely to remain the dominant driver of changes in flood risk, at least over the coming decades. This suggests that measures that aim to reduce current vulnerability and manage other drivers of risk, such as risk-averse land-use planning and effective drainage systems, can be highly effective ways of reducing risk both today and over the next few decades. Crucially, where possible, one can aim to avoid decisions that would worsen climate-induced risks; e.g., paving over green spaces in cities.

One of the most cost-effective approaches to reducing risk today and in the future is through community-scale hard-infrastructure projects, including flood walls, flood storage and embankments. Where community-scale resistance is not available or comprehensive, property-level resistance measures may be desirable. These types of hard-infrastructure investments tend to be long-lived and locked-in; that is, they are costly to change once implemented. This makes decisions today potentially sensitive to climate change. However, for many (particularly, existing) properties and settlements, this may be the only viable way to resist flooding. As shown in the previous sections, options are available to increase flexibility. An urgent need for policymakers is to assess the benefits of incorporating flexibility into decisions that are already in the pipeline to avoid locking in future vulnerability and potential maladaptation.

Other measures can also be an important part of the adaptation mix; including natural ecosystem-based flood control (e.g., flood storage and drainage measures) and property-level resilience (e.g., sand bags or dry flood proofing). A no-regrets goal of policy may be to support effective autonomous adaptations, like property-level resilience but also insurance or natural drainage solutions (e.g., green paving or vegetation to enhance drainage or slow runoff). Some autonomous adaptations have been traditionally underused in UK flood risk management [7], in part due to lack of information, low risk perception, or the perception that flood risk management is the responsibility of either government or the insurer. Implementing policies that help to overcome these barriers to autonomous adaptation can be an effective form of adaptation [12].

Finally, in considering the roles of different measures, it is important to consider their co-benefits and tradeoffs holistically. For example, hard infrastructure can have negative impacts on local ecosystems. In addition, risk-averse land-use planning can sometimes have tradeoffs with development objectives; e.g., the need for new housing.

6.5.2 Case Study: The Thames 2100 Project

The UK Environment Agency's Thames Estuary 2100 (TE2100) project provides a real-life example of adaptation decision making under uncertainty applied to a long-lived infrastructure decision with high sunk costs. The objective of TE2100 was to provide a plan to manage flood risk in London and the Thames Estuary over the next 100 years. This section provides only a limited overview of the project as an example and focuses only on the coastal flood risk elements; for a fuller description by the project team see Lowe et al. [30], Reeder et al. [34], Haigh & Fisher [21], and the TE2100 website [18].

Today the Thames region is well protected but the impacts of an unmitigated storm surge flood would be disastrous in terms of lives lost, property damaged, and economic disruption.[12] Central London is protected by the Thames Barrier, which was opened in the 1980 s to protect against at least a 1-in-1,000 year return period storm surge. The system was originally designed to last to 2030. The TE2100 project aimed to examine whether and when the system might need to be modified and to provide a forward plan to 2100. The large-scale (£1.6 to £5.3 billion[13]) and irreversibility of the potential investments, the risks associated with failure, and the

[12] The last time that central London was inundated was in 1928. The last major flood occurred in 1953, when there was extensive damage and loss of life in the eastern part of the Estuary.

[13] Costs of the no-minimum and greatest-response (new barrage) adaptation options under the central sea level rise scenario.

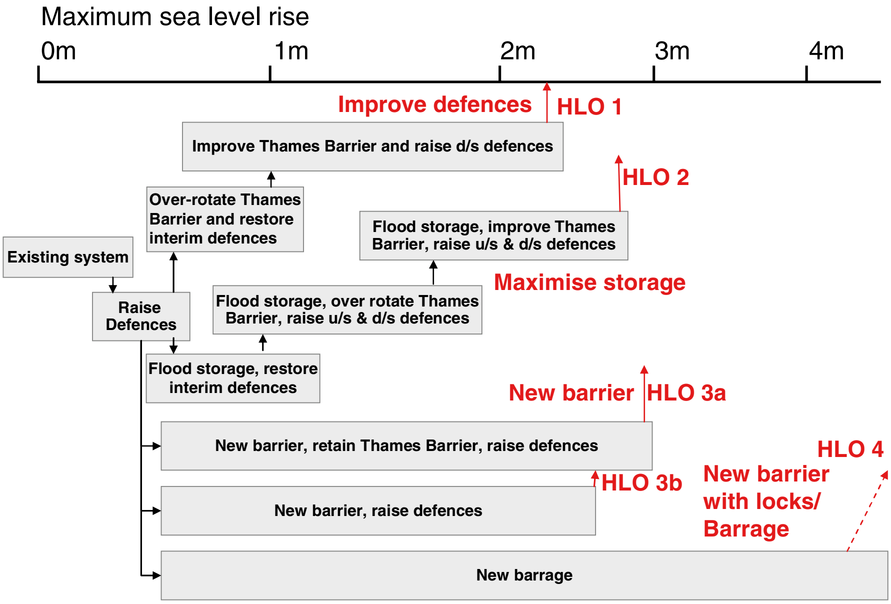

Fig. 6.5 High-level adaptation options and pathways developed by TE2100, shown relative to threshold- level increases in extreme water level. The blue and red lines show possible high-level options; particular options pathways that can be followed in response to different thresholds [21]

long lifetimes and lead times of the infrastructure, together meant that the investments are likely to be highly sensitive to climate change; the potential for maladaptation is significant. The plan needed to consider not only growing hazards due to climate change, but also the parallel pressures and uncertainties related to ongoing development within the flood plain.

The adaptation decision-making process followed a similar structure to that presented in Sect. 6.4. It began by mapping the context of the decision problem; including working with stakeholders to characterize the objectives and constraints of adaptation, mapping current vulnerabilities to flooding in the Thames Estuary (including current flood protection standards), screening future sensitivities to climate change and other drivers, and identifying available adaptation options. An important output of this phase was a mapping of the ranges of sea level rise over which different adaptation options were appropriate. This is shown schematically in Fig. 6.5. The measures were sequenced to create four possible high-level adaptation paths, each appropriate under different scenarios.

The choice of adaptation path was found to be highly sensitive to mean sea level and storm surge projections, which are notoriously uncertain [30]. The risk screening suggested that the maximum potential increase in sea level (which included consideration of processes not currently in models) is 2.7 m by 2100; at this level of sea level rise, only paths HLO3 and HL04 would be suitable. The limit to adaptation, where desirable protection levels could be compromised and some retreat from the Estuary may be required, was considered to be at around 5 m sea level rise [34].

The pathway options were appraised against multiple decision criteria, including the net present value of investments and environmental impact. A *quasi*-real-options analysis was employed to weigh-up the benefits of incorporating flexibility into the adaptation strategy. *Quasi* is used because, given the nature of the uncertainties, the real-options analysis was extended to test the sensitivity of adaptation plans to ambiguity over future sea level rise, thus informally incorporating some elements of a robustness-based approach.

The outcome of this appraisal is an adaptation plan that focuses on sequencing a suite of measures in order to manage current risk while maintaining the flexibility to cope with the range of possible future sea level rise. Specifically, the strategy sets out a range of no-regrets early actions, such as extending the lifetime of existing infrastructure, as well as a 40-year investment plan detailing a decision process for upgrading the existing flood management system, with a set of decision points conditional on observations of sea level rise (below). The appraisal showed that taking no-regrets measures first would cost-effectively buy time before it is necessary to make a more irreversible decision (e.g., a new and expensive barrier), thus allowing time to monitor and learn to gain additional information in order to make an improved decision.

An important advance of the TE2100 project was the use of thresholds, lead times, and decision points to select and sequence options conditional on observations of sea level rise. For each adaptation option, the project assessed the key threshold of climate change at which that option would be required (e.g., the extreme water level), the lead time needed to implement that option, and therefore the estimated decision point to trigger that implementation (in terms of an indicator value, such as the observed extreme water level, with an uncertainty range) (Fig. 6.6).

Based on current projections, the initial decision point is expected to come around 2050, at which time decision makers would choose between the more irreversible options, such as upgrading the existing Thames Barrier or building a new Barrage, with the benefit of an additional 40 years of knowledge about climate change and sea level rise. One of the reasons that this flexibility was available is that following the 1953 floods, the Thames Estuary has had tight development controls, restricting new property developments in high-hazard regions. If monitoring reveals that water levels (or another indicator, such as barrier closures) are increasing faster (or slower) than predicted under current projections, decision points may be brought forward (or put back) to ensure that decisions are made at the right time to allow an effective and cost-beneficial response. This creates an uncertainty on the timing of the decision point that can be estimated based on the range of projections.

This example highlights the potential benefits of a real-options approach. However, Fig. 6.4 shows that real-options analyses do depend on trustworthy probability distributions. In many cases, such data will be unavailable. In TE2100, this was overcome by sensitivity testing the options to a range of assumptions about sea

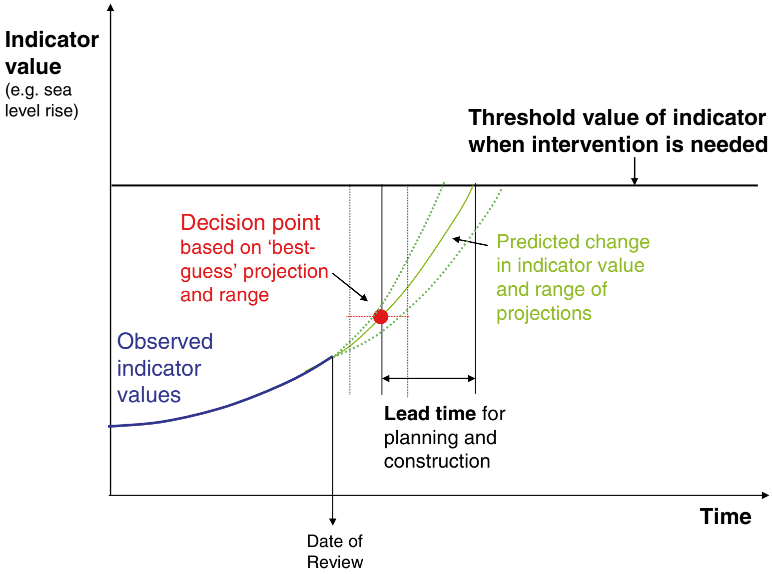

Fig. 6.6 Schematic diagram of the thresholds, lead times, and decision points approach used in TE2100 [21]

level rise and designing a strategy that is robust to these uncertainties. Another potential challenge is that these types of decision analyses can be resource-intensive. However, where the stakes are high, this type of careful, substantive, and clear appraisal, with a full assessment of sensitivities and uncertainties, is often necessary to justify a flexible approach.

6.6 Learning the Lessons for Robust Adaptation Planning

Sect. 6.3 highlighted that the key principle for building robust adaptation strategies under deep uncertainty is maintaining flexibility, or conversely, avoiding (as far as possible) decisions that will limit flexibility to cope with future changes. The flood management case study, as well as case studies on food, water and ecosystems described in Ranger et al. [33], point toward a number of lessons for maintaining flexibility:

- In many cases, a range of no-regrets options are available that reduce risks under any scenario and do not limit flexibility to cope with future climate change. These can have an immediate benefit in terms of risk reduction and can also enhance long-term flexibility; in the TE2100 case, this involved extending the

lifetime of existing flood management infrastructure. Another approach is better managing other trends in risk, such as new developments in flood plains or growing water consumption, which often are dominant drivers of risk, at least in the short term; as illustrated in the TE2100 case, managing these drivers reduces risk and increases long-term flexibility to cope with climate change. Building broad resilience to climate risks, including early warning systems and financial safety nets, is an additional flexible approach with immediate benefits.
- Only in a few cases will a decision maker be forced to make the difficult choice between potentially high-regrets options due to climate change uncertainties, where the benefits of options depend strongly on uncertain future climate states. These will usually be limited to urgent, long-lived, and inflexible decisions with high sunk costs (e.g., some infrastructure investments with high capital costs). These types of decisions tend to be limited to public-sector and large private sector organizations (e.g., water and energy companies).
- Even where decisions are long-lived with high sunk costs, such as large-scale infrastructure projects, flexible options or strategies are often available and can be shown to be desirable. For example, even in the case of the upgrade to the Thames Barrier, a decision with high sunk costs, long lead times, and a lifetime of 100 years, an approach was identified that is robust to climate change uncertainties.

This analysis suggests that many elements of adaptation plans, particularly in the near-term, are not necessarily highly sensitive to climate change uncertainties. Further, for long-term decisions, through employing a broad range of adaptation measures, considering flexibility up front, and sequencing measures to best cope with uncertainty, it is possible to build robust adaptation plans.

Of course, as in decision making in other areas, difficult choices may still need to be made in managing tradeoffs among different objectives and constraints. There could be challenges arising from constrained resources, inadequate institutional decision-making structures, or lack of information. However, these challenges are not unique. In many cases, these decisions are no more difficult than decisions in any other areas of public policy.

Another important conclusion that arises from the case studies involves the timing of decisions. Like greenhouse gas mitigation, a delay in some forms of adaptation could mean greater costs down the line. For example, policy and spending decisions are made every day that could increase future vulnerability to climate change or reduce flexibility to adapt, potentially locking in future unnecessary costs. In addition, in some highly vulnerable areas like ecosystems, inaction could result in severe and potentially irreversible impacts even on short timescales. This suggests two priorities for adaptation:

- *Avoid near-term significant and/or irreversible impacts*: prioritize adaptation for sectors or actors with high vulnerability to weather and climate change in the near-term. For example, ecosystems have been shown to have a high sensitivity to even small changes in climate and are susceptible to irreversible effects, such as the loss of species.

- *Avoid locking in future vulnerability*: Identify adjustments, measures, investments and policies that could increase potential vulnerability to climate change or reduce the flexibility to adapt. This includes, for example: new long-lived projects, such as infrastructure or new housing developments; and policies that might create barriers to autonomous adaptation, such as agricultural subsidies.

Beyond this, there are a number of adaptation options that are time-sensitive or have immediate benefits and so may be desirable to implement today:

- *No-regrets measures*, in particular, measures with significant co-benefits across sectors, such as ecosystem solutions to flood control and water quality; measures to better manage current climate variability or build general resilience; measures to manage other drivers of risk; and policies that promote effective autonomous adaptation; for example, raising awareness and providing information, or removing broader barriers to autonomous adaptation, such as agricultural subsidies.
- *Options with long development lead times*, such as research and development of new technologies (e.g., new crop varieties); restoring degraded habitats to create new ecosystem networks; and upgraded water management systems.

Finally, early action is required to build the human, institutional, and informational capacity to adapt effectively. This includes building skills, institutional and governance structures, monitoring systems, and appropriate delivery networks.

6.7 Summary

This chapter began by considering whether adaptation presents a unique challenge for decision makers. It has shown that adaptation will share many of the same challenges as other areas of policy, including lack of information, resource constraints, and differing values and perspectives on what are acceptable risks and what is successful adaptation. Sect. 6.3 describes the major new challenge introduced by climate change as deep uncertainty about the future evolution of climate. In adaptation, decision makers can no longer rely on the past as an adequate guide to the future. Given the benefits of anticipatory over reactive adaptation, this means that to be effective climate risk management must shift from a paradigm of backward-looking risk assessment to one based upon forecasting current and future risk. This exposes decisions to additional uncertainties and requires the use of a broader set of tools for adaptation.

The chapter discusses two broad approaches to dealing with the deep uncertainty in projections; the first involves optimizing a decision based on the best available data and the second involves forming a strategy that is robust to the deep uncertainties. Each strategy involves tradeoffs. For example, where there are deep uncertainties the first approach is exposed to risks of maladaptation. Conversely, the second approach may mean upfront additional costs. A desirable approach may take elements from both sides. The central principle of achieving robust adaptation is to maintain flexibility to cope with a range of future climates, or conversely, to avoid decisions that would inhibit flexibility. Flexibility can be either built into an adaptation measure itself or achieved through sequencing a suite of adaptation measures, as in the TE2100 case.

The cases presented and drawn on in this chapter suggest that in many cases, adaptation will be no more challenging than many other areas of public decision making. In many cases, a broad range of desirable options are available that are robust to climate change uncertainties; these include no-regrets measures, from better managing current weather to managing non-climate trends in land-use or demand, and also measures with strong co-benefits with other objectives, such as the conservation of ecosystems. Only in a few cases will a decision maker be forced to make a potentially difficult choice between high-regrets options on the basis of climate change uncertainties. These will usually be limited to long-lived, inflexible decisions with high sunk costs, such as public infrastructure projects. However, even in these cases, it may be possible to develop a flexible solution through sequencing decisions, as in the TE2100 case.

The chapter identifies two priorities for public policy around adaptation: avoid near-term significant and/or irreversible impacts and avoid locking in future vulnerability. Like greenhouse gas mitigation, a delay in some forms of adaptation could mean greater costs down the line: policy and spending decisions are made every day that could lock in future risks. Similarly, delays in action in some areas could lead to significant and irreversible impacts, such as loss of species. Other priorities include building capacity for adaptation, seizing desirable no-regrets options, and initiating adaptations with long lead times, such as research and development of new crop varieties.

Finally, while this chapter has focused on adaptation alone, adaptation is not an objective or process that should be considered in isolation. Adaptation is one part of broader decision making; for example, it is an integral part of sustainable development, land use planning, resource and risk management, and environmental sustainability. Adaptation in isolation will miss important synergies and tradeoffs with other areas; for example, adaptation acting in isolation will be less able to effectively seize co-benefits with other policies and measures, such as ecosystem restoration; mainstream climate-resilience into new developments, investments, and strategies; and manage complex tradeoffs across sectors, such as land-use development, flood risk management, agriculture, and water quality. Risks, opportunities, objectives and measures should be considered within the broader context of decision making and implementation.

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Chapter 7
What Social Science Can Teach Us About Local Adaptation

S.M. Kane

Abstract Adaptation to climate change is the focus of great attention in public policy decision making, international economic development, and international negotiation. This chapter offers thoughts on lessons learned from social sciences and examines vocabulary and the intrinsic nature of human coping and adaptive behavior taken from different disciplines. A suggestive review of 15 years of scholarly progress offers insight into key lessons and identifies knowledge gaps. A meta-analysis of existing study results is recommended to enrich existing knowledge about the social dimensions of adaptation, especially at the local scale and for the poorest citizens, and to help create the lens through which current empirical studies of local adaptation can be interpreted and utilized. The insights from a meta-analysis can be utilized directly in studies of adaptation costs, enabling decision makers to more ably plan the future direction of adaptation expenditures.

7.1 Introduction

In the past 15 years, the field of adaptation to climate change and variability has evolved from a relatively small area of research and a strong political and social concern of people living in countries vulnerable to El Nino/Southern Oscillation (ENSO) into a very active area of inquiry by scientists, practitioners, international negotiators, and government officials. The topic is under serious discussion and planning at many levels of governance in Organisation for Economic Co-operation and Development (OECD) countries (New York City and the State of California, in the United States, Canada, and the United Kingdom) in response to increasing misgivings about the viability of an international program on mitigation and the

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framework for international negotiation [16]. In addition, there is a growing perception that mega-disasters have grown in scale and number in the past decade or more, and some may be associated with changes in climate [7, 25].

At a practical level, environmental nongovernmental organizations (NGOs) are working closely with international agencies dedicated to disaster reduction, humanitarian response, and economic assistance to build adaptation into national work plans. Their goals are to encourage local governments in less industrialized countries to integrate planning for natural disasters, economic development, and adaptive response to climate change and climate variability.

This chapter offers thoughts on what social sciences and risk analysis can teach us about local adaptation. The first section examines vocabulary and the intrinsic nature of human coping and adaptive behavior taken from different disciplines. A suggestive review of 15 years of scholarly progress follows in the second section. Knowledge gaps and a core recommendation for further study close the chapter.

7.2 Words, Definitions, and Human Behavior

In the most recent assessment of the Intergovernmental Panel on Climate Change (IPCC), definitions of adaptation and adaptive capacity are distinguished from those relating to impacts, vulnerability, and sustainability:

- *Adaptation* is the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities [8].
- *Adaptive capacity* is the ability of a system to adjust to climate change (including climate variability and extremes), moderate potential damages, take advantage of opportunities, or cope with the consequences [8].

Consideration of dynamic processes of learning, feedback, and coping can further enhance these definitions.

Adaptation has very specific, technical definitions in the social sciences, each of which conveys the notion of change, learning, and coping in the face of altered circumstances, new information, and new experiences. Adaptation inherently involves dynamic processes whereby information is updated over time in decision making (for additional background see Rayner and Malone [20] for a thorough, scholarly treatment of social, individual and cultural precepts for social decision making and choice relating to climate change; also see Stern [24] for a review of literature on individuals' environmentally significant behavior).

Looking at definitions of adaptation (that is, about individual and social behavior) from topical areas other than climate change, one can also begin to appreciate the role of experimentation and nonlinear movement that precede significant adaptive movement. Adaptive responses are not necessarily smooth, gradual, or completely well understood in advance. There is an element of innovativeness by those who are making adaptive choices, those who design adaptive policy strategies, and those who execute the strategies.

In the following sections, definitions are quoted from the fields of business, foreign policy, and psychology. The characteristics articulated in the definitions are important to incorporate more fully into discourse about managing climate risk and facilitating adaptation responses.

7.2.1 Adjust to New Information and Experiences: Example from Psychology

In a popular psychology dictionary, Kendra Cherry [5] offers this definition:

> Adaptation is a term referring to the ability to adjust to new information and experiences. Learning is essentially adapting to our constantly changing environment. Through adaptation, we are able to adopt new behaviors that allow us to cope with change.

7.2.2 For New Ideas, Provocation and Discontinuity: Example from Business Innovation

Richard Watson [28] quotes from several authors on the theme of evolutionary innovation. He quotes Nicholas Negroponte's account of MIT's academic programs, where they mix different disciplines, saying that

> …. New ideas do not necessarily live within the borders of existing intellectual domains. In fact they are most often at the edges and in curious intersections.

He mentions Edward de Bono's view on the need for provocation and discontinuity. In order to come up with a new solution you must first jump laterally to a different start or end point.

Finally, he quotes from Charles Darwin:

> …It is not the strongest of the species that survives, nor the most intelligent, but the one most responsive to change.

7.2.3 Handle Unexpected Changes for a World That Is Regenerative and Diverse: Example from Foreign Affairs

Cascio [4] comments on the resilience of societies:

> …How can we live within our means when those very means can change, swiftly and unexpectedly, beneath us? We need a new paradigm. As we look ahead, we need to strive for an environment, and a civilization, able to handle unexpected changes without threatening to collapse. Such a world would be more than simply sustainable; it would be regenerative and diverse, relying on the capacity not only to absorb shocks like the popped housing bubble or rising sea levels, but to evolve with them.

7.3 A Look Back over 15 Years of Progress

In 2000, Kluwer published a collection of papers on social adaptation to climate change and variability as a special issue in *Climatic Change* and as a book with the same title [9]. The idea for the collection was spurred by discussions about integrated assessment of climate change held at meetings convened by the International Institute for Applied Systems Analysis and Stanford University's Energy Modeling Forum. The broad premise was that studies on adaptation were hard to access and study for a variety of reasons. Scholarly articles are published in separate literatures and peer review journals. Research enterprises are organized separately because of different funding sources and organizational structures. And differences persist in the interpretation of the concept itself. The collection brought together the work of geographers, economists, decision analysts, and climate scientists. The collection stands as a reflection of the scholarly but fragmented state of literature existing at the time. Its lessons closely track those from other research enterprises [13].

Five of the general lessons raised in the collection are directly relevant to the questions about local adaptation and global climate change that were the focus of the 2010 NATO Workshop held in Hella, Iceland.

- Institutions are important.
- The integration of mitigation and adaptation policy responses in policy evaluation and program planning is essential.
- Flexibility in decision making and policy development is essential for successful adaptation to climate change and variability.
- Social, cultural, legal, and political information are central to rigorous decision making.
- Careful use of vocabulary facilitates comparative research in applied research across disciplines and improves the integrity of integrated assessment modeling and policy making.

Two additional lessons are important in the consideration of local adaptation and have not been as visible in experts' writings.

- Adaptation to multiple stressors is an important approach when examining adaptation to climate change. Adaptation by both human and natural systems can be studied effectively using portraits of characteristics [22].
- The effects of climate, the ability to adapt, and the effects of adaptation policies on poor people are not well understood, even though studies are undertaken in poor countries. Poor populations in industrialized and non-industrialized countries have different lives and day-to-day concerns from more wealthy populations in the same countries [12].

Evolving literature and the state of knowledge about adaptation have been evaluated by the IPCC and summarized most recently in the Technical Summary and Summary for Policy Makers from the Fourth Assessment of the IPCC [8, 18, 19]. The IPCC found that large gaps in knowledge about adaptation and adaptation processes persist. At the same time, demand is growing at all levels of governance for guidance to help facilitate flexible decision making for adapting to climate change with an integrated risk reduction approach, especially for the poorest countries.

A few long-term efforts in economics and other social sciences have been initiated recently. These research enterprises follow from a traditional system of inquiry with analysts working in groups pooling ideas and expertise, separate from citizens who are located in areas vulnerable to adverse effects of climate variability. The studies are:

- A focused program of study by the OECD and World Bank to examine the economic costs of adaptation [1].
- A new long-term study, the Earth System Governance Project, has been initiated by the International Human Dimensions Programme on Global Environmental Change. It is organized in five analytic problem areas:

    1. Architecture of governance
    2. Agents that drive governance
    3. Adaptiveness of governance
    4. Accountability and legitimacy of governance
    5. Access to goods and their allocation as determined through governance [2]

7.4 Knowledge Gaps and a Recommendation to Examine Evolving Literature

7.4.1 A Recommendation for Systematic Review of Studies and Plans for Adaptation from the Perspectives of Scholarship and Policy

Many studies of adaptation to climate change are underway. Given the knowledge gaps related to the mechanisms by which adaptation actually occurs over time, analyzing these studies could provide much needed information for policy makers as well as the research community. This is particularly true for adaptation by the poorest citizens.

The rationale for assembling a data base for review is part economic, part academic, and part good public administration. Many scarce financial resources are being requested for adaptation funding assistance. Decisions about the direction and amounts of assistance provided would be informed by results from a review of studies and the existence of an adaptation deficit [3] can be better addressed. Moreover, a meta-review of studies could generate practical information for sponsors leading to improved design for future studies on adaptation to climate change.

Systematic review is needed to understand more fully factors affecting the private and social costs of adaptation. Too little is known about how adaptation occurs differentially in market economies, non-market economies, and different types of governance found around the world. Examination of local and regional studies could yield insight into migration, development of institutions, actual risk management, and factors important in private and public decision making.

A review of studies would help decision makers at all levels of governance better interpret the results of the studies for those issues or geographic areas closest to them. For example, a new Adaptation Atlas has been developed by Resources for the Future and was unveiled at the Copenhagen negotiating session in 2009 [27]. The Atlas uses state-of-the-art technology to upload adaptation study information and provide access to users around the world. Study results and other descriptive information are oriented along several different dimensions. Developing and incorporating a decision context into the Atlas is challenging, but desirable, so that users can best evaluate the fit of the study results for their particular areas and circumstances.

Selection of the exact goals of a review will dictate the type of data required, methodological approaches, and scale of the effort necessitated.

7.4.2 Financial Support and Access to Study Data Needed for a Meta-review

Extending research efforts or initiating new ones to evaluate local and small regional scale studies with a focus on the poorest citizens can be costly. Permission to access and utilize full study data would need to be pursued. Given the mix of study types, data would be in nonstandard form, and often in descriptive format, posing a challenge for researchers and sponsors.

7.4.3 Evaluation Methods

The studies have different goals for citizen participation, building sustainability and resilience, reducing vulnerability and risk exposure, promoting adaptation investment, and sharing knowledge.

Systematic review would have to address another type of heterogeneity; that is, the mix of quantitative and qualitative methods. Qualitative studies yield rich, contextual information that cannot easily be compared. Quantitative studies yield information useful in prediction and integrated study. Evaluation of such a mixed data set would require expertise from anthropology, sociology, political science, risk and judgment, geography, history, social psychology, and economics, enriching the existing community of researchers and research organizers and sponsors. In addition, expertise in the area of qualitative research, especially methodological innovation [17], would be required.

7.4.4 Input into Risk Analysis

Results from a meta-review of studies could inform risk models. The behavioral component in risk analyses, treating interconnectedness and feedback between individual, private sector, and public sector decision making—especially for the poorest citizens—could be sharpened using the results of a meta-study. A fuller understanding of the individual's ability to affect the risk posed by his or her choices to reduce exposure is needed, especially for the poorest citizen. See Kane and Shogren [9] and Shogren and Crocker [23] for one area of risk analysis, endogenous risk, which can be used to formally study links between relevant disaster management, climate adaptation, climate mitigation, and other policies that can either complement or hinder the goals of adaptability to climate variability and change.

The areas of risk communication and perception are highly pertinent to understanding individual and collective adaptation response to climate change. The concept of social trust has been explored [10, 11, 15] in other contexts of environmental risk, and could be advanced with results from a meta-analysis of climate adaptation studies.

7.4.5 A Growing Source of Studies Can Be Reviewed

Several international programs are generating studies that can be reviewed. Two dozen studies were funded by the Global Environment Facility program, Assessments of Impacts and Adaptations to Climate Change [14]. The main purpose was to better understand the nature of vulnerability to climate change, and to examine adaptation strategies. Another goal was to build greater local capacity for scientific and technical inquiry and narrow the divide between science and policy [14]. To help support the negotiating process and raise associated funds for less industrialized countries, the UN Development Program has identified hundreds of projects to promote adaptation planning and investment through National Adaptation Plans of Action (NAPAs) [26]. The UNFCCC requires less industrialized countries to undertake NAPAs to gain access to the adaptation fund. A core goal of the NAPA program is to prioritize investments needed by the most vulnerable countries. Many NAPA projects are underway.

The International Institute for Environment and Development (IIED) in London has a program of work focusing on the most vulnerable populations at the local level, sharing knowledge among practitioners, decision makers and community citizens wherever possible [21]. The concept of community-based adaptation encompasses community level development, research, and practices.

Several studies were conducted for the Economics of Climate Adaptation Working Group sponsored by the Global Environment Facility [6]. And finally, many studies have been undertaken as part of the effort undertaken by the UN and World Bank to understand risks posed natural disasters [29]; the purpose of the program of work is to integrate risk management from climate risk and that posed by natural disasters.

7.5 Conclusions

Adaptation is the focus of much attention in policy discussions, international economic development, and international negotiation. A financial challenge lies ahead in funding and executing scientific studies about adaptation processes at the same time that large investments in adaptation are being promoted actively in the policy community. A systematic review can yield important information for decision making about the future direction of adaptation expenditures, provide insight into social dimensions of adaptation that are not as yet well understood, especially at the local scale and for the poorest citizens, and help create the lens through which current empirical studies of local adaptation can be interpreted and utilized.

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Chapter 8
Risk Management Practices

Cross-Agency Comparisons and Tolerable Risk

I. Linkov, M. Bates, D. Loney, M. Sparrevik, and T. Bridges

Abstract The inevitable public unease in the wake of large infrastructure failure prompts questions regarding how to properly define and manage the risks of various engineered activities to socially acceptable levels. A changing climate may add additional vulnerability to infrastructure and thus should be considered in risk management strategies. Current implementations of risk management processes differ across public agencies, but often rely on a concept of Tolerable Risk. Tolerable Risk is a numerical value for the boundary—in a continuum of management alternatives—below which risk is tolerated to secure societal benefits, though engineering interventions may be still be necessary and proper to achieve higher degrees of protection. This chapter gives an overview of risk management and introduces the Tolerable Risk framework, reviews and summarizes risk management frameworks for several federal and foreign agencies, and recommends key features and necessary steps for a Tolerable Risk framework implementation. The ideas in this chapter draw extensively from a March 2008 interagency workshop on Tolerable Risk sponsored by the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, and the Federal Energy Regulatory Commission, and attended by several additional federal and foreign agencies [33].

8.1 Introduction

The Society for Risk Analysis defines risk as the "potential for realization of unwanted, adverse consequences to human life, health, property, or the environment" [31]. Calculation of risk, especially in environmental settings, is conducted

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through risk assessments that place numerical values on the risk associated with a particular option or event. This requires evaluating both the probability that a particular event (for example, 1 ft of sea level rise) will occur and the likely impacts (for example, in terms of dollars or families displaced) should the event occur. In other words, risk is measured both in terms of the likelihood and severity of impacts of a hazardous event. The National Research Council defines risk assessment as a process that involves identifying all relevant hazards, linking each hazard to a potential adverse impact, assessing society's exposure to the hazards, and estimating the hazards' likely cumulative impact on society [22]. Though risk assessments identify and quantify risk, they give no insights into whether the identified risks are socially acceptable.

Risk management applies society's risk tolerance and preferences to risks by identifying, selecting, and applying specific risk-reducing strategies. All risks are not created equal, and proper risk management recognizes that different levels of risk warrant different reactions. Some risks are high enough that action must always be taken to reduce their magnitude. Other risks are low enough that they can generally be considered negligible. Yet other risks are high enough to warrant reductions but low enough that reductions should only be undertaken when considered reasonable in the context of project costs, other risks, and social preferences. Nuanced risk management often differentiates between individual risk (which relates to one person's increased risk from a project or event), societal risk (which aggregates individual risks to set a maximum for the total number of people who may be affected), and project-failure risk (which relates to the expected number of failures per project per year), each of which may require a different risk management strategy.

The key components of risk management are:

1. Establishing the context and determining risk thresholds
2. Risk identification and risk assessment
3. Risk treatment, developing risk reduction and mitigation strategies
4. Monitoring and review

Communication and consultation with internal and external stakeholders should take place at each stage of the risk management process. By implementing these risk management strategies, public agencies can reduce or mitigate risks to socially acceptable levels. A general approach to risk management implementation has been standardized under ISO standard 31000 [12].

8.1.1 Risk Management Criteria

Morgan and Henrion [19] describe four primary types of risk management criteria and techniques: utility-based, rights-based, technology-based, and hybrid, each of which contain several variations founded on similar principles (Table 8.1). Utility-based techniques trade risk reduction with another quantity, typically money, to determine the optimal balance between risk protection and incurred costs.

Table 8.1 Types of risk management criteria/techniques [19]

Utility-based (ALARP) criteria	
Deterministic cost-benefit	Estimate the costs and benefits of the alternatives in economic terms and choose the alternative with the highest net benefit.
Probabilistic cost-benefit	Incorporate uncertainties to estimate the costs and benefits of the alternatives in economic terms and choose the alternative with the highest expected net benefit.
Cost-effectiveness	Select a desired performance level, perhaps on noneconomic grounds, and choose the option that achieves the desired level at the lowest cost.
Bounded/constrained cost	Do the best you can within the constraints of the maximum budget society is prepared to devote to the activity.
Maximize multi-attribute utility	Rather than use monetary value as the evaluation measure, multi-attribute utility involves specifying a utility function that evaluates outcomes in terms of all important attributes (regardless of units, including uncertainties and risks). The alternative with maximum utility is selected.
Minimize chance of worst possible outcome/ Maximize chance of best possible outcome	Political and behavioral considerations frequently employ the use of such criteria, which often go against society's long-term best interest.
Rights-based criteria	
Zero risk	Independent of the benefits, costs, and magnitude of the risks, eliminate all risks, or disallow risk introduction.
Bounded/constrained risk	Constrain the level of risk so that it does not exceed a specific level or, more generally, so that it meets a set of specified criteria. This is done independent of the costs and benefits of any alternatives.
Approval/compensation	Allow risks to be imposed only on people who have voluntarily given consent or who have been properly compensated.
Approved processes	Require compliance with specific agency-approved processes that have been shown indirectly reduce risks by avoiding risky behavior.
Technology-based criteria	
Best available technology	Use the best available technology to reduce risk to the lowest level possible. As the meaning of *best available* is often economically determined, this may become a modified utility-based technique.
Hybrid criteria	
Hybrid	Some combination of utility-, rights-, and technology-based criteria used jointly for decision making.

Rights-based criteria acknowledge that, for certain sources of risk, people are entitled to receive an absolute level of protection. Technology-based criteria recognize that risk reduction is often limited by the available technology and that risks should be mitigated using the best technologies available. Hybrid criteria combine various aspects of utility-based, rights-based, and technology-based criteria to evaluate risks with a more nuanced approach.

Of the utility-based techniques, cost-benefit analysis is the most widely used. Cost-benefit analyses seek to monetize the benefits of risk reduction and identify the point where risk protection most outbalances project costs (all relevant project inputs and effects must be monetized). Cost-benefit analyses may be deterministic, using known data, or probabilistic, incorporating uncertainty. When benefits are not easily quantifiable, a cost-effectiveness analysis can identify the least costly method of achieving a desired performance goal. If funding is a limiting factor, a bounded-cost approach seeks to achieve the greatest risk reduction with a set capital expenditure. Multi-attribute utility methods can identify the best tradeoffs when several non-monetized factors must be compared, even when units are incongruous. Though usually little more than a political ploy, another utility-based approach is simply to minimize the likelihood of the worst-case scenario or maximize the likelihood of the best-case scenario.

Rights-based risk management criteria focus on constraining risk to specific values. The zero-risk criterion takes this to the greatest extent possible, mandating that all risks must be eliminated and that none may be introduced. Bounded-risk (or constrained-risk) criteria allow some risk to exist but do not allow risk levels to grow above a predetermined value. Approval/compensation-based techniques only allow risks to exist if those who bear them have given their consent or have been appropriately compensated for bearing the risk. The establishment of approved processes treats risks indirectly by mandating compliance with a specified set of agency-approved procedures designed to avoid risky behavior by those introducing the risk.

Technology-based criteria seek to implement the best available technology and accept whatever risk results as the lowest risk possible. This requires an additional process be set up to identify the best available technology, a process which itself may be utility-, rights-, or technology-based. Judgments regarding technology are often made using cost-benefit analyses or by finding the technologies that achieve the greatest risk reduction (rights-based). Hybrid methods merge utility-, rights-, and technology-based criteria to produce risk reductions that are fitting for special circumstances and are unique to the implementation details of each particular project.

8.1.2 The Tolerable Risk Framework

The Tolerable Risk (TR) framework provides a risk management structure for public agencies worldwide. TR was first conceived by the British Health and Safety Executive (HSE) during its work on the safety of nuclear power plants [60]. The TR framework breaks risks into acceptable, unacceptable, and tolerable categories, separated by numerical boundaries (Fig. 8.1). By evaluating risks in relation to predetermined TR thresholds, the decision of when to implement the chosen risk management strategies becomes transparent and unambiguous.

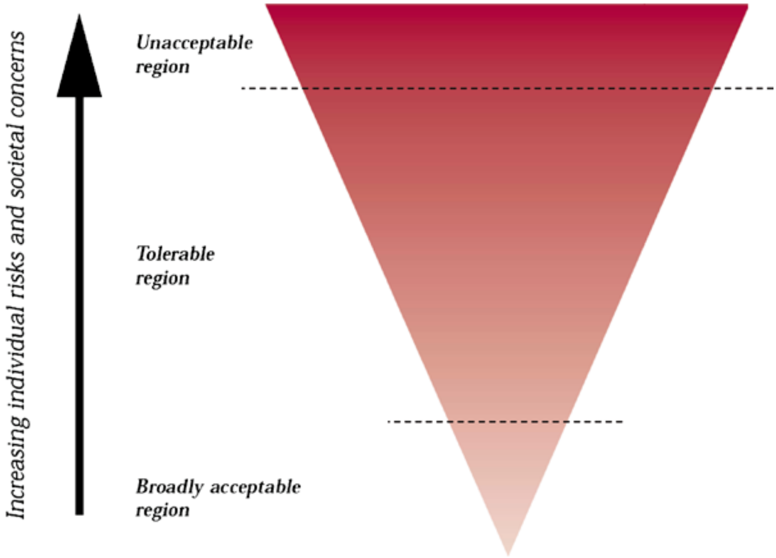

Fig. 8.1 Conceptual categories of risk within the TR framework [61]

Under the TR framework, an Acceptable Risk is a risk for which the probability of occurrence is so small or for which the consequences are so slight that individuals or groups accept it willingly. Actions to further reduce such risks are usually not required. In contrast, an Unacceptable Risk is a risk so high that society is unwilling to bear it to receive the promised benefit. When identified, measures must be taken to reduce an unacceptable risk's likelihood or consequence of harm. Occupying the middle ground between the acceptable and the unacceptable are Tolerable Risks, non-negligible risks that have not been reduced to an acceptable level but which society is willing to bear in order to secure the benefits associated with the risky activity. Tolerable risks must be reduced to levels as low as is reasonably practicable (ALARP), meaning until costs or other feasibility concerns prohibit further reductions. Given the tradeoffs necessary in achieving the ALARP condition, TR is most often used in conjunction with the utility-based ALARP considerations from Morgan and Henrion's list of risk management criteria (Table 8.1). The goal of risk management is to push risks from the unacceptable, through the tolerable, and into the broadly acceptable region.

Development of numerical boundaries separating risk regions is an important step in applying the TR framework [61]. Rather than relying on subjective judgment to differentiate risk regions, the HSE outlines risk thresholds loosely based on risks commonly accepted by the public, such as the risk of death from rock climbing, high-risk professions, and traffic accidents [60]. The HSE determined that the highest level of risk the general public would bear in order to receive some benefit was roughly 1 in 10,000 (deaths per year per capita), and that risks with a chance of less than 1 in 1,000,000 (deaths per year per capita) were generally considered by the public to be inconsequential [60, 61]. Similar metrics can be defined for risks not related to human health, such as for those associated with environmental harm.

Application of the TR framework to risk management is relatively straightforward. After TR thresholds are in place and the governing ALARP considerations are chosen, risk assessments are conducted to place any identified issue within a TR risk region. If the identified risk falls within the broadly acceptable region, no further action is necessary, and if it falls in the unacceptable or tolerable regions, risk-reducing solutions must be developed. For tolerable risks, each solution undergoes an analysis to determine if taking further action is practicable under the organization's chosen risk management criteria. For unacceptable risks, risk-reducing strategies must be employed until the risk enters the tolerable region. Once in the tolerable region, risk solutions continue to be implemented until the ALARP condition is satisfied. All risks are analyzed on an ongoing basis to ensure that tolerable risks remain ALARP, that broadly acceptable risks remain in the broadly acceptable region, and that further unacceptable risks are not introduced. As TR thresholds and the "reasonably practicable" condition are not globally defined, it is left to the practitioner to determine which risk thresholds and risk management strategies are appropriate for each individual implementation [4, 16].

Implementing a TR framework often involves comparisons among risk metrics for which units rarely align (e.g., comparing risks from increased climate variability to risks from sea-level rise). This has led to great diversity in TR implementation, and federal risk management has historically never been unified under a single framework. Instead, each agency has created its own risk management practices based on social trends, expert knowledge from the risk management community, and agency goals within the statutory context. The U.S. has undergone several periods of risk management implementation, moving from an initial concept based on zero risk to periods focused on best technological practices, cost benefit tradeoffs, and again on zero risk [27]. Presently, U.S. and foreign agencies are increasingly embracing the TR framework, and ongoing conversations between federal agencies are laying the foundation for a more standardized, interagency approach to TR implementation [21, 35].

8.2 Risk-Based Decision Making by Public Agencies

This section compares current risk management strategies among eight federal and foreign agencies, giving special attention to areas where components of the TR framework are and are not incorporated. The basis for this comparison is a March 2008 Tolerable Risk Workshop hosted by the U.S. Army Corps of Engineers (USACE), the U.S. Bureau of Reclamation (Reclamation), and the Federal Energy Regulatory Commission (FERC) [33]. From attendee agencies, comparisons are included for Reclamation, the U.S. Environmental Protection Agency (EPA), the U.S. Federal Aviation Administration (FAA), the U.S. Food and Drug Administration (FDA), the

National Aeronautical and Space Administration (NASA), the Nuclear Regulatory Commission (NRC), and the HSE. Details for the Norwegian Petroleum Safety Authority (PSA) are also included. Sources are drawn from both workshop documents and the literature. The goal of this comparison is to develop an understanding of how each agency conceptualizes and incorporates the TR framework in its risk management activities and to summarize the risk thresholds and ALARP considerations that are commonly implemented (Table 8.4).

8.2.1 Bureau of Reclamation

Reclamation owns and operates approximately 350 reservoirs in the western U.S. [37]. Founded in 1902, Reclamation's mandate was to tame the West by capturing and storing water for irrigation and human consumption. Several dam failures throughout the 1970, most visibly that of the Grand Teton Dam, spurred the passage of the Reclamation Safety of Dams Act of 1978, calling for the Department's Secretary to take risk mitigation actions at Reclamation facilities. Additionally, in 1979, the ad hoc Interagency Committee on Dam Safety developed a series of *Guidelines for Dam Safety* in a document first establishing safety procedures for federally owned dams. These legislative mandates and committee recommendations have been incorporated by Reclamation into a quantitative risk management system based on TR-like thresholds [36].

Reclamation currently divides risk into separate categories for risk of project failure and societal risk. To manage the risk of project failure (e.g., for ensuring water delivery reliability and protecting public assets), a single TR threshold of 10^{-4} (failures per year per project) delineates the boundary between unacceptable and tolerable risks (no broadly acceptable threshold is specified). Reclamation breaks with the traditional TR framework in that even unacceptable risks of project failure are not subject to mandatory reductions. Unacceptable risks are instead subject to ALARP risk reduction and are given higher funding/timeline priorities within the project portfolio. Probabilistic cost-benefit and multi-attribute utility considerations are loosely applied to determine when ALARP risk levels have been reached [20, 36].

Societal risks (e.g., the risk of mortality from uncontrolled flooding to populations residing downstream of Reclamation projects) are defined with both unacceptable and acceptable risk regions, in a process that more closely follows the traditional TR framework. Unacceptable societal risks lie above a threshold of 10^{-2} (deaths per year per project) and require expedited action. Broadly acceptable societal risks fall below a threshold of 10^{-3} (deaths per year per project) and require no action above whatever is deemed reasonable and prudent by the decision maker. Between the unacceptable and broadly acceptable thresholds are tolerable risks. These are considered by Reclamation for ALARP risk reductions within the normal budget and maintenance cycles and should typically be dealt with within 7 years. Broadly acceptable risks may also be considered for ALARP reductions, pending funding. Subjective cost-benefit and multi-attribute utility considerations are also used to determine ALARP levels for societal risks [36].

In regions with low population densities, Reclamation discards the tolerable risk thresholds and ALARP considerations used for societal risk and instead relies on a bounded-risk approach that limits the population's exposure to risks of no greater than 10^{-3} (deaths per year per project) [36]. This explicitly recognizes that populations in low-density areas may be exposed to a disproportionately high portion of what would otherwise be a generally acceptable societal risk and should be protected, regardless of cost.

Baseline risks at each Reclamation facility undergo a comprehensive review every 6 years, in which Reclamation scores dams on the basis of static, hydrologic, and seismic risks and on operational and maintenance criteria. Facilities with the riskiest scores are prioritized for funding with a bounded cost constraint that allocates resources across the entire project portfolio, to achieve the greatest overall risk reductions, nationwide [5].

8.2.2 Environmental Protection Agency

The EPA has long been involved with human-health and environmental risk management [44]. Early EPA risk management was strictly qualitative, but quantitative methods were introduced in the 1970s, starting with a vinyl-chloride risk assessment and published guidelines for evaluating carcinogens [14]. After the National Research Council's publication of *Risk Assessment in the Federal Government: Managing the Process*, the EPA quickly began formalizing guidelines for specific types of risk assessment [22]. These guidelines are still considered best practices for human-health and environmental risk assessments among many today, and are used in risk assessments by many federal agencies [44].

Due to the diversity of EPA duties, the use of risk management thresholds and ALARP considerations varies greatly with project purpose and type. While other decision factors are often involved in shaping EPA regulation, specific risk thresholds form a basis for many EPA risk management duties. Carcinogenic risks (e.g., from hazardous air pollutants or at Superfund sites) are generally considered unacceptable if they lie above a threshold of 10^{-4} (cancer incidents per year per capita) and broadly acceptable if they lie below a threshold of 10^{-6} (cancer incidents per year per capita) [38, 41, 42, 43]. These thresholds were originally envisioned for a Benzene air-pollution standard, but have recently been applied more broadly. It is also notable that the EPA looks at both the magnitude and distribution of risks and develops standards to protect sensitive, rather than average, individuals. In practice, EPA risk thresholds are not constant [34] and the agency often couples utility-, technology-, and approval-based ALARP considerations with relevant economic, legal, social, technological, political, and public interest attributes to guide its risk management decisions [43].

Systemic toxicity risks from non-carcinogenic substances are separately managed through daily oral Reference Doses (RfD) or inhalation Reference Concentrations (RfC) because the toxic effect depends on substance accumulation rather than mutation and uncontrolled cellular growth. The RfD/RfC system uses human and animal research data to establish the daily intake amounts of a substance that will not cause harm over the course of a lifetime [39, 43]. These values are scaled from a no-observed-adverse-effect level (NOAEL) and impose no judgments about risk tolerability. For composite non-carcinogenic substances, total risk is captured through a hazard index that normalizes and combines RfDs/RfCs to incorporate effects from individual chemicals [40].

Depending on the situation, risks of dosage above or below the RfD/RfC may or may not be deemed acceptable, but should be managed so as to cause no harm [38, 41]. The EPA emphasizes that RfD/RfC values are an extension of carcinogenic risk management considerations and are not standalone criteria; yet, without clearly defined thresholds and ALARP considerations, risk management for non-carcinogenic substances requires case-by-case judgment. For yet other cases (e.g., airborne asbestos exposure), a zero-risk approach is applied under which all exposure is considered detrimental and no risk is tolerated [45].

8.2.3 Federal Aviation Administration

The FAA manages aviation and rocket risks separately, though neither include traditional tolerable risk thresholds. Commercial aviation risks are assessed in relation to historical casualty rates, allowing regulators to establish relative safeties by comparing new components with their predecessors. Historical commercial aviation risks range from 10^{-6} to 10^{-9} (failures per flight per component) for general aviation, though risks as high as 4×10^{-6} (failures per flight per component) have been shown for short-term flights [2, 15]. The probability that any one component will fail is determined by dividing the historical casualty rate by the number of individual components that must fail to achieve system failure.

Risk management for commercial rocketry is more standardized. Firm thresholds for unacceptable risk are codified in FAA regulations for both private human spaceflights via reusable launch vehicles and traditional commercial launches, though no lower threshold differentiates tolerable from broadly acceptable risks. Human spaceflights in reusable launch vehicles must maintain individual risk below an unacceptable threshold of 10^{-6} (deaths per flight per capita) and societal risk below an unacceptable threshold of 3×10^{-5} (expected deaths per flight per capita), where the less stringent societal threshold permits additional takeoff and landing debris [28]. The FAA requires traditional launches to keep all casualties below 3×10^{-5} (deaths per mission per capita) [46]. Licensees within both categories must demonstrate that the risk standards have been met prior to receiving a license.

Though no tolerable risk region is specified, the FAA integrates utility-based ALARP considerations (deterministic and probabilistic cost-benefit analysis and cost-effectiveness analysis) in its risk assessments for both types of projects. FAA risk assessments may be either qualitative or quantitative, though both develop a Comparative Safety Assessment by ranking alternatives for each high-consequence decision.

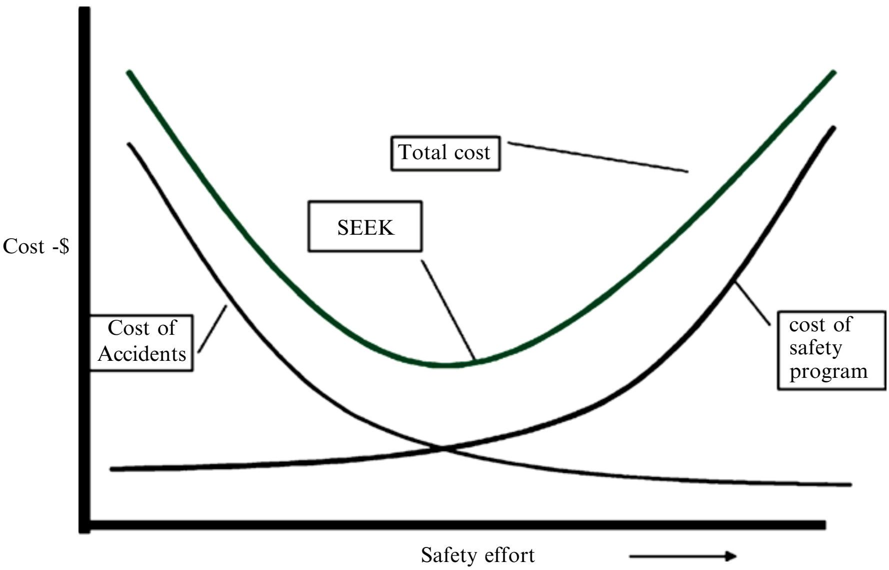

Fig. 8.2 A cost-benefit approach balances improved safety against other project costs [47]

As a type of cost-benefit analysis, these assessments must "compare each alternative considered (including no action or change, or baseline) for the purpose of ranking the alternatives…" and "assess the costs and safety risk reduction or increase (or other benefits) associated with each alternative…" [47]. Despite the use of ALARP risk management methods, overall use of a TR framework is minimal and neither human nor commercial spaceflight is held to stringent tolerable risk thresholds [47] (Fig. 8.2).

Though the FAA does endorse quantitative methods, the agency converts all quantitative data to qualitative data for decision making. Risk-related decisions are typically made through a risk matrix, categorizing outcomes by both probability and effect. Any risk scoring high in the matrix (typically in the top right corner) is mitigated through additional action. Any risk below the right corner is considered acceptable, though actions may still be taken to reduce acceptable risks on a case-by-case basis [47].

8.2.4 *Food and Drug Administration*

The FDA was one of the first agencies to implement the traditional TR framework and is largely responsible for popularizing the common 10^{-6} risk threshold. This threshold stems for a 1961 proposal by Mantel and Byan to use 10^{-8} as a de minimus risk level, an idea that the FDA eventually adapted and adopted with its acceptable-risk threshold of 10^{-6} for packaged meat products, as introduced in the its final rules for *Chemical Compounds in Food-Producing Animals* in 1979 [13, 17, 48]. However, since the FDA first adopted TR thresholds, the agency has abandoned large parts of the TR framework and now relies on ALARP risk reductions for all regulated products, regardless of risk.

The FDA manages risk differently for the food and drug industries. For food products, the FDA generally manages risk by requiring compliance with specific low-risk processes approved by the agency [6]. These processes are based on scientific findings, precautionary beliefs, industry concerns, and/or congressional legislation, and can be quite detailed [49]. For milk pasteurization, for example, the FDA requires compliance with specific pre- and post-pasteurization handling practices and dictates the temperatures and length of time of each pasteurization stage [52]. Increasingly, food risks are also being managed through a bounded-risk approach that allows the FDA to set an unacceptable risk threshold and enables providers to implement their own strategies to meet that constraint [6].

For drug products, the FDA determines risks to be ALARP through cost-benefit analyses that weigh the advantages and disadvantages of candidate drugs. As drug risks are widely legislated, these cost-benefit analyses often have a deterministic component, though agency-approved processes and probabilistic analyses are also employed. Drug applications are approved if the agency considers the benefits to outweigh the drawbacks and are otherwise rejected or subjected to additional study [6, 11]. When firm TR thresholds are present, ALARP risk levels are established through risk-minimization plans submitted with the candidate application [50, 51].

8.2.5 National Aeronautical and Space Administration

Through the Apollo and early shuttle programs, NASA relied on Failure Modes and Effects analyses in risk assessments identifying components critical to mission safety and recommending them for design improvements. With the loss of the Challenger shuttle, reprimands from the House of Representatives and the Slay committee led NASA to develop a more quantitative approach to risk assessment [53]. NASA's current approach to risk management relies heavily on risk matrices and employs both qualitative and quantitative risk assessments in an iterative adaptive management process [10, 32].

NASA specifies individual risk management criteria for each project. TR thresholds are not numerically defined but are thought of as a series of iso-risk contours within a risk matrix (Table 8.2). Risk falling outside of the unacceptable contour must be reduced while risks falling between the broadly acceptable and unacceptable contours are reduced until ALARP. Bounded cost constraints and deterministic/probabilistic cost-benefit analyses are often used to determine when risks are ALARP [9, 54].

Table 8.2 Risk matrix with iso-risk contours (Following NASA)

	Likelihood estimate				
Consequence class	Likely to occur	Probably will occur	May occur	Unlikely to occur	Improbable
Catastrophic	1	1	2	3	4
Critical	1	2	3	4	5
Moderate	2	3	4	5	6
Negligible	3	4	5	6	7

8.2.6 Nuclear Regulatory Commission

The NRC initially managed risk by applying prescriptive requirements developed through experience, test results, and expert judgment [59]. With the publication of the *Reactor Safety Study* in 1975, NRC regulations began to quantify risk systematically (e.g., in WASH-1400, NUREG/75-014). The NRC's 1994 *Probabilistic Risk Assessment Implementation Plan* began to move towards a TR framework and was superseded in 2000 and 2007 with new guidance documents that each successively advocated TR to a greater degree [57–59].

The current risk management structure of the NRC is founded on a rights-based, constrained-risk approach to delineating fixed (non-ALARP) risk boundaries. The NRC specifies that nuclear risks should be equivalent to or less than those created by other forms of electricity generation and that nuclear energy should pose "no significant additional risk to life and health" [55]. Specifically, NRC risk objectives delineate acceptable increases in risk over background levels through quantitative health (QHO) and subsidiary risk objectives (SRO). The QHO for personal risk establishes an acceptable composite increase of prompt death for those living within a mile of a civilian nuclear power plant as 0.1% of the sum of all background risk (prompt deaths per year per capita). Similarly, the QHO for composite societal risk of cancer death is set at 0.1% above background cancer risk (cancer deaths per year per capita). SROs are benchmarks toward QHO goals, defining acceptable risks for physical aspects of facilities. Example SRO include the risk of reactor failure and large radioactive release, set at 10^{-4} and 10^{-6} (failures per year per reactor) respectively [55]. Risks managed through the current implementation plan are broken into three main areas—reactor safety, materials safety, and waste management—each requiring probabilistic risk assessments [58].

Facility modifications must also meet risk thresholds. Alterations are measured for their effect on various facility baseline risks. For example, any potential change affecting the reactor core damage frequency (RCDF) must be evaluated. If the RCDF is initially below 5×10^{-3}, small changes in risk of less than 1×10^{-6} are approvable. If the initial RCDF is below 1×10^{-4}, then changes in risk of up to 1×10^{-5} are permissible. Similar risk-adjustment structures govern facility modifications impacting Large Early Release Frequencies and other measured quantities [18].

Risk thresholds apply continuously throughout the lifespan of a reactor. Inspections measure the risk associated with various plant activities [26]. If thresholds are found to be exceeded, the plant must take mitigating action to improve the facility's safety system and may also suffer fines [56].

8.2.7 UK Health and Safety Executive

The HSE developed the TR framework and actively regulates risk throughout UK industry and society. The HSE grew out of the 1972 Robens Committee tasked with reforming regulation to better protect the population [3]. Finding previous risk management structures piecemeal and narrowly focused on single objectives, the Robens committee made recommendations that were incorporated into the UK Health and Safety at Work etc. Act of 1974, redesigning the risk-regulatory framework of the UK and officially establishing the HSE. In 1988, in response to the Sizewell B nuclear power plant hearings, the HSE first published risk standards for nuclear power stations that incorporated the TR framework [60]. As this initial document was revised and republished, the TR framework was expanded to include all industrial risks [61].

HSE regulations take a holistic approach towards risk and are implemented through TR thresholds and various ALARP criteria. As previously mentioned, the HSE has established a general unacceptable risk threshold of 10^{-4} (deaths per year per capita) and a general broadly acceptable risk threshold of 10^{-6} (deaths per year per capita) [61]. With tolerable risks, ALARP reductions are made based on considerations including cost-benefit analyses, best practices, uncertainty, potential adverse consequences, technological developments, and regulatory feasibility [3]. The HSE ensures compliance with its regulations with inspections throughout its jurisdiction in England, Scotland, and Wales.

8.2.8 Norwegian Oil Industry

The Norwegian oil industry has strongly embraced risk assessments and emergency preparedness measures in the design and operation of offshore and onshore oil facilities [25]. The PSA is the agency that regulates major accidental and environmental risks for the Norwegian oil industry, by defining both normative regulations and detailed risk management frameworks. The PSA was created in 2004 from a split of the Norwegian Petroleum Directorate (founded in 1972), with the intention of separating the supervision of petroleum health and safety from the management of petroleum resources [24]. The PSA has developed separate risk management frameworks for the risk of accidental harm to humans and structures, the risk of accidental harm to the environment, and the risk of continuous environmental harm from normal operations [8]. The PSA defines risk acceptance criteria (RAC) that are the main instruments for determining which risk reduction measures should be implemented, though the ALARP principle has gained increased focus in recent years [1, 62].

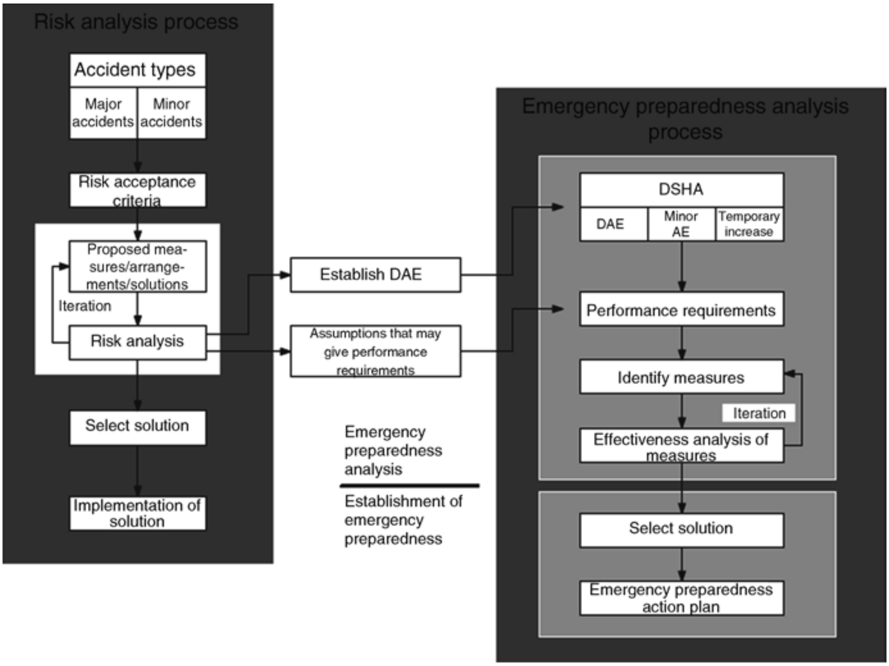

Fig. 8.3 The Norwegian risk analysis and emergency preparedness analysis processes [25]

One major achievement of risk management in the oil industry was the introduction of the NORSOK standards for risk analysis and emergency preparedness. The present version is from 2001 and describes a process for using quantitative risk analysis to arrive at solutions in accordance with the RAC [25]. Typical risk-reducing measures include physical measures like fire insulation, deluge systems, pressure release systems, and also organizational procedures like safety training and establishing a safety culture. Based on the results of each risk analysis, multiple emergency scenarios are developed from which specific emergency preparedness measures are selected (Fig. 8.3).

For major accidental risk (i.e., of loss of human life or health or significant structural damage), it is important to note that the NORSOK standard does not specify threshold values for the RAC. Likely due to the political infeasibility of placing a valuation on human life, the regulations give only normative recommendations on acceptance criteria and leave the specific acceptance criteria to be formulated by the individual oil companies [8, 62]. Threshold values for major accidental risk are determined by each company using individual risk criteria like the Fatal Accident Rate, defined as the expected number of fatalities per 10^8 h of exposure, the Potential Loss of Life, which calculates the expected number of fatalities per year, or risk matrices. Group risks are also defined by some companies using F-N curves that show a relationship between the cumulative frequency (F) of an event and the number (N) of fatalities expected [29, 62].

In contrast with the RAC for major accidental risk, the RAC for major environmental risk do contain specific thresholds in a framework developed by the Norwegian Oil

Table 8.3 RAC limits for environmental-damage type and scope of operations [62]

Environmental damage	Field specific frequency limits per year:	Installation specific frequency limits per year:	Operational specific frequency limits per operatison:
Minor	$<2\times10^{-2}$	$<1\times10^{-2}$	$<1\times10^{-3}$
Moderate	$<5\times10^{-3}$	$<2.5\times10^{-3}$	$<2.5\times10^{-4}$
Significant	$<2\times10^{-3}$	$<1\times10^{-3}$	$<1\times10^{-4}$
Serious	$<5\times10^{-4}$	$<2.5\times10^{-4}$	$<2.5\times10^{-5}$

Industry Association. These environmental RAC are based on the principle that the duration of environmental damage shall be insignificant in relation to the expected time between such damaging occurrences. Categories of environmental damage include Minor, for accidents with expected recovery between 1 month and 1 year, Moderate, for accidents with expected recovery between 1 and 3 years, and Significant, for accidents with expected recovery between 3 and 10 years (Table 8.3) [62]. Environmental RAC are also defined based on the size of the operation. With an inverse relationship between strictness and scope and according to the ALARP principle, the criteria are defined more strictly for any individual operation than for the whole oil field [7, 62].

Environmental risk assessments, the results of which are compared to the environmental RAC, involve estimation of release frequencies, rates, and durations of spill and calculation of oil drift and damages, which often vary by season. The final risk estimation is often presented as the ratio between risk and acceptance criteria for the species of interest in each damage category, for relevant species and seasons [7, 29].

Lastly, the Norwegian regulations recognize that there are certain operational environmental risks inherent in oil production. Whereas accidental environmental risk is regulated based on accident return periods, risk from continuous exposure is regulated through discharge permits (e.g., for discharges of produced water, chemical use, and air emissions). The Norwegian Pollution Control Act of 1981 states that all pollution is illegal unless specifically allowed by law, regulations, or individual permits. This zero-harmful-discharge philosophy encourages companies to make substitutions for less harmful chemicals and environmentally beneficial processes, like using produced-water reinjection instead of produced-water disposal [23]. Environmental impact is calculated with environmental impact factors (EIF) addressing the aggregated potential eco-toxicological impact from the entire operation, rather than looking only at individual contributions. The oil industry uses these EIF calculations to prioritize risk-reducing measures and to compare environmental impacts between locations—thus making it possible to prioritize risk reduction based on cost-benefit allocations at the whole-field scale [30].

8.2.9 Summary

Though there is currently no coordinated effort to adopt standardized risk management approaches across federal or international agencies, several notable trends can be seen (Table 8.4). Many of the agencies in this review have adopted a TR or

Table 8.4 Summary and threshold values and of management criteria (ALARP or otherwise) within the risk management frameworks of surveyed agencies

Regulating agency	Threshold values	Risk management criteria
Bureau of Reclamation	Project failure: *Broadly acceptable* 10^{-4} failures per year per project Societal risk: *Unacceptable* 10^{-2} deaths per year per project *Broadly acceptable* 10^{-3} deaths per year per project	*ALARP*: Bounded cost Probabilistic cost-benefit *Non-ALARP*: Bounded risk (Consideration of other factors)
Environmental Protection Agency	*Unacceptable* 10^{-4} cancer incidents per capita/year *Broadly acceptable* 10^{-6} cancer incidents per capita/year	*ALARP*: Various utility-based *Semi-ALARP:* Best available technology Approved processes (Consideration of other factors)
Federal Aviation Administration	Aviation (historical values): *Unacceptable* 10^{-6} failures per flight per component *Broadly acceptable* 10^{-9} failures per flight per component Rockets: Individual risk: *Broadly acceptable* 10^{-6} deaths per flight per capita Societal risk: *Broadly acceptable* 3×10^{-5} deaths per flight per capita	*ALARP*: Deterministic cost-benefit Probabilistic cost-benefit Cost effectiveness
Food and Drug Administration	None	*Non-ALARP*: Approved processes
National Aeronautical and Space Administration	Set on an individual project basis	*ALARP*: Deterministic benefit cost Probabilistic cost-benefit Bounded cost
Nuclear Regulatory Commission	Individual risk: *Broadly acceptable* 0.1% of general prompt death background risk Societal risk: *Broadly acceptable* 0.1% of general cancer death background risk	*Non-ALARP*: Constrained risk
UK Health and Safety Executive	*Unacceptable* 10^{-4} deaths per year per capita *Broadly acceptable* 10^{-6} deaths per year per capita.	*ALARP*: Deterministic cost-benefit Probabilistic cost-benefit

(continued)

Table 8.4 (continued)

Regulating agency	Threshold values	Risk management criteria
Norwegian Petroleum Safety Authority	Set by each company in coordination with the regulating authorities, typically through: *For major accidental risk:* PLL, FAR, individual risk, F-N curves *For accidental environmental risk:* Return periods depending on environmental damage *For operational environmental risk:* Discharge permits, zero harmful risk	*ALARP:* Deterministic cost-benefit Probabilistic cost-benefit *Semi-ALARP:* Quantitative Risk Acceptance Criteria (RAC)

modified-TR framework specifying threshold values for the unacceptable and/or broadly acceptable risk regions. Threshold values are most often set to around 1 in 10,000 for the unacceptable region and 1 in 1,000,000 for the broadly acceptable region. The high similarity of threshold values between agencies owes to early threshold popularization by the FDA and to a common threshold derivation from socially accepted risk and general background risk, as discussed by the HSE [60, 61]. Risk among the surveyed agencies is often also divided into multiple categories, with different thresholds specified for individual, societal, and/or project risks.

The majority of the surveyed agencies apply utility-based analyses to determine when ALARP conditions have been met, though some agencies avoid the ALARP approach altogether. Notable exceptions include the NRC, which uses a constrained-risk approach, and the FDA, which requires compliance with specific approved processes. Reclamation, the EPA, and the Norwegian PSA use combinations of ALARP, semi-ALARP, and non-ALARP considerations to tailor their risk management strategies to individual projects. Of the utility-based risk management criteria used, cost-benefit ALARP considerations are the most common.

8.3 Discussion and Recommendations

8.3.1 Features of a Robust TR Framework

Key features which must be present in a TR framework to ensure proper function include threshold values, management criteria, review timeframes, and communicability. Clearly defined risk thresholds provide managers with target values, trigger safety actions when risks rise above acceptable limits, and serve as explanatory tools that managers can refer to when questioned about project design choices. Robust threshold values must either be derived comprehensively from background risk or compared to equivalent types of risk that are commonly accepted or rejected. With either threshold definition strategy, the implemented TR framework must delineate scientifically why thresholds are set at particular values relative to the definition mechanism.

It is also important that a robust TR framework have management criteria and review processes that are as clearly defined as the threshold values. Management criteria establish priorities between the unacceptable and broadly acceptable regions and tend to be much more subjective than threshold values. Therefore, when management criteria are employed, explicit justification must accompany each criterion's application. Once a risk management strategy or TR level is established, it must be periodically reviewed to insure continuing compliance with existing regulations and the feasibility of further risk reductions. Reviews are vital for long-term risk management at infrastructure sites.

Defining TR threshold values scientifically rather than with professional judgment allows the public to have a firm understanding of the protection levels offered. When risk values fall within the tolerable region, the public must also have clear knowledge of the reasons why further risk reductions are not feasible. If a TR framework is implemented but the public is not made aware of the identified risk thresholds and probability justifications, the framework is likely to fall short of achieving its maximum potential effect.

8.3.2 Steps Towards TR Implementation

Though the implementation of TR varies between regulating authorities, features such as focus parameters, risk thresholds, and management criteria remain largely consistent across implementations. These features, together with identified review timeframes and communication planning, can considerably reduce project risks and raise public awareness of safety improvements in infrastructure development.

The following multi-step process is envisioned to aid public agencies in implementing TR frameworks to successfully manage climate-change risks and public perceptions of these risks. Transitioning to a TR framework will likely require a process consisting of: defining the focus parameters for risk reduction, defining threshold values, selecting risk management criteria, selecting review timeframes, applying TR to facilities, and communicating with the public.

8.3.2.1 Definition of Focus Parameters for Risk Reduction

Defining risk management goals and metrics helps to identify which areas merit consideration for reductions in risk. The scope of these metrics can include individual, project, and/or societal risks, covering topics such as the loss or degradation of life, health, personal property, national security, or the environment. By defining these risk reduction parameters, later risk management is made more transparent and is focused into clearly defined areas. For offshore oil and gas development, for example, key goals have included reduction in risks of both the occurrence and impacts of oil spills and reductions in major accidents, injuries, and fatalities associated with offshore operations. But specifying the goals is just one dimension of this task; the other is to develop the metrics for measuring trends and performance relating to these goals. For example, what criteria should be used to define "major accidents?" Are injuries best tracked as a ratio of incidents to number of hours worked, by oil production activity, or by some other metric?

8.3.2.2 Definition of Threshold Values

Defining threshold values provides unacceptable and broadly acceptable risk limits for each focus parameter, using easily communicable and scientific means. In addition to specifying the thresholds themselves, this process should determine if the identified values are static across the project portfolio or must be redefined for each project location. Clearly defined threshold values are important for identifying in which situations additional risk reductions are mandatory, potentially warranted, or unnecessary. Defining such thresholds is not always straightforward nor without controversy. For example, thresholds for establishing "unacceptable" risk levels for exposure to air, water, or soil contaminants are sometimes contested as being either too high or too low. However, in many instances, it is not the threshold, per se, that is contested. Rather, significant disagreements often surface regarding the analytic tools and assumptions for assessing whether some action or exposure falls within the range of tolerable risk.

8.3.2.3 Selection of Risk Management Criteria

For each project, consideration needs to be given as to which methods, such as cost-benefit analysis, or which criteria will be used to determine if project risk levels are ALARP, and to choose between risk reduction measures. Selection of ALARP considerations sets the framework for the application of risk reduction methods. Along with the selection of considerations, implementation guidelines also need to be developed.

8.3.2.4 Selection of Review Timeframes

Review timeframes are meant to ensure continued compliance with ALARP and threshold values. Among other cases, timeframes will likely need to be developed to review facilities already considered ALARP but subject to new data from periodic risk assessments, to assess the progress made towards compliance by facilities above the maximum threshold and to determine the maximum time available to implement ALARP upgrades for facilities already within the tolerable region.

8.3.2.5 Application of TR to Facilities

When threshold values, ALARP considerations, and review timeframes are in place, the TR framework should be applied to existing infrastructure facilities to ensure compliance or to bring facilities into compliance. Because of the scale associated with such an endeavor, it is likely that the application of a TR framework to a new facility might be accomplished over several years.

8.3.2.6 Communication with the Public

In parallel with implementing the TR framework, agencies should consider developing communication strategies to inform the public about the risk management strategies in place. Such efforts might include developing visual aids for explaining the calculated risks (e.g., explaining the TR triangle, comparing project to equivalent levels of risk), developing explanations of the ALARP considerations employed, and sharing the results established through ALARP reductions. Simple, effective communication strategies are essential for public understanding of the actual level of protection provided by infrastructure and civil works projects.

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Chapter 9
Adaptation to Climate Change

More Than Technology

R.J.T. Klein

Abstract The traditional view of adaptation to climate change tends to assume that a national government is responsible for implementing technological adaptation measures (e.g., seeds, dams, irrigation schemes), which are selected on the basis of specific knowledge of future climate conditions. This view has been widely challenged but is still prevalent within sectors dominated by engineering, such as water and coastal management. The purpose of this chapter is to show that while technology has an important part to play in climate adaptation, its effectiveness relies on it being part of a broader strategy that acknowledges uncertainty and addresses the underlying drivers of people's current and future vulnerability. Such a strategy requires the integration of adaptation with human and economic development efforts.

9.1 Coastal Adaptation to Climate Change: An Overview

Many low-lying coastal areas around the world are densely populated and attract major economic activity and investment. These areas are often susceptible to hazards such as storm surges and coastal erosion. Society has a long history of coping with and preparing for these hazards, and technology has been instrumental in doing so. Technology can reduce society's vulnerability to coastal hazards in three basic ways [15]:

- Protect: reduce the risk of the event by decreasing its probability of occurrence
- Retreat: reduce the risk of the event by limiting its potential effects
- Accommodate: increase society's ability to cope with the effects of the event

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Over the course of this century and beyond, the effects of climate change and associated sea level rise on coastal areas will include increased flooding and inundation, increased erosion, saltwater intrusion, rising water tables impeding drainage, and loss and change of wetlands and coral reefs [23]. The same three strategies of protect, retreat, and accommodate can be followed to adapt to the effects of climate change, including application of the same technologies as are used today.

As discussed by Klein et al. [18, 21], the emphasis of coastal risk management has traditionally been on protecting developed areas using hard structures. The technologies required to plan, design, and build these structures depend on their scale and level of sophistication. On a small scale, local communities can use readily available materials to build protective structures. However, these communities may lack the information to know whether or not these structures and their design standards are appropriate and acceptable.

Until recently it was rarely questioned whether or not a country's coastline could be protected effectively. It has become clear, however, that even with massive amounts of funding not all coastlines can be protected by hard structures. In addition, increasing awareness of unwanted effects of hard structures on erosion and sedimentation patterns has led to the growing recognition of alternative approaches, including soft protection (e.g., beach nourishment, wetland restoration), and the strategies of accommodate (e.g., building houses on stilts, planting salt-tolerant crops) and retreat (e.g., relocating buildings, establishing setback zones).

In spite of this trend to consider adaptation options other than hard protection, many structures are still being built without a full evaluation of the alternatives. A reason could be that hard structures are more tangible and hence appeal more strongly to the imagination of decision makers and—by their visibility—may be perceived to provide more safety and hold the sea at bay forever. This chapter argues that coastal adaptation consists of more than merely increasing the design level of existing coastal protection structures, and that reliance on technology is not always an effective way of reducing people's vulnerability to coastal hazards. The chapter calls on engineers to join forces with social scientists and other experts to design and implement integrated strategies that include non-technological adaptation options and consider climate change along with other issues of concern to coastal societies.

9.2 Technology: Part of the Solution

Adaptation to climate change is defined by the Intergovernmental Panel on Climate Change [14] as an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Past advances in many human systems, such as food production, water supply and sanitation, and infrastructure design, have been made possible because of technological innovation and deployment. Likewise, technology will be an important part of successful adaptation to climate change. Much of the technology needed for climate adaptation is already available; technological innovation will serve to increase the effectiveness and reduce the cost of existing technology, as well as to create new technological options.

In a technical paper aimed at informing international climate change negotiators of the role of technology in climate adaptation, Klein et al. [17] distinguished between traditional technologies, modern technologies, high technologies, and future technologies. Traditional technologies consist of the many approaches that have been developed and applied throughout the centuries to adapt to weather-related hazards; examples include the building of houses on stilts and the construction of bunds, levees and dykes to protect against flooding. Modern technologies are those that have been created since the onset of the industrial revolution in the late eighteenth century. They make use of new materials and chemicals, new ways of generating power and facilitating transport, and improved designs.

High technologies derive from more recent scientific advances, including information and communication technology, earth observation systems and geographical information systems, and genetically modified organisms. Future technologies are those that are yet to be invented or developed. Examples might include a vaccine against malaria and crops that need little or no water. The limits to such future technologies, if any, are in the human imagination and ingenuity.

In a chapter of an IPCC report on technology transfer, Klein et al. [18] provided examples of traditional, modern and high technologies available for coastal adaptation to climate change (see also Klein et al. [21]). They made the point that technology can be employed not only to protect coastal populations, but in any of the four basic steps that comprise the process of adaptation to climate change [20]:

- Information development and awareness raising
- Planning and design
- Implementation (i.e., protect, retreat, accommodate)
- Monitoring and evaluation

Table 9.1 presents examples of technologies for information development and awareness raising, while Table 9.2 provides the same for the three aforementioned forms of coastal adaptation: protect, retreat, and accommodate.[1]

Tables 9.1 and 9.2 also illustrate that existing technologies for coastal adaptation vary from hard to soft, from simple to highly complex, from inexpensive to very costly, and from locally available to requiring international technology transfer. Each type of technology has its own advantages and disadvantages. The suitability of any given technology for adaptation will depend on the location of deployment, the degree of climate change, and the prevailing social, economic, and environmental conditions and management practices within a country or community.

[1] These tables are simplified versions of the ones provided in the IPCC chapter, but they serve to illustrate the diversity of technologies available. More details can be found in Klein et al. [18, 21].

Table 9.1 Examples of technologies to collect data, provide information, and increase awareness for coastal adaptation to climate change

Application	Technology
Coastal system description	
Coastal topography and bathymetry	Mapping and surveying
	Videography
	Airborne laserscanning (lidar)
	Satellite remote sensing
Wind and wave regime	Waverider buoys
	Satellite remote sensing
Tidal and surge regime	Tide gauges
Relative sea level	Tide gauges
	Historical or geological methods
Absolute sea level	Satellite remote sensing
	Tide gauges, satellite altimetry and global positioning systems
Past shoreline positions	Historical or geological methods
Land use	Airborne and satellite remote sensing
Natural values	Resource surveys
Socio-economic aspects	Mapping and surveying
Legal and institutional arrangements	Interviews, questionnaires
Socio-cultural factors	Interviews, questionnaires

9.3 Technology: Part of the Problem

The previous section has shown that many existing technologies can be used to adapt to climate change and associated sea level rise in coastal areas. This does not mean, however, that every vulnerable coastal country and community has access to the technology that would best suit its needs, or to the knowledge that is required to develop or implement that technology. Effective coastal adaptation by these countries and communities could therefore benefit from increasing current efforts of technology transfer [18].

Improving access to technologies for adaptation is gradually becoming a priority for governments. For example, as part of the recent Cancun Agreements, negotiated under the United Nations Framework Convention on Climate Change (UNFCCC), countries jointly established a Technology Mechanism that explicitly considers adaptation along with mitigation (i.e., reducing greenhouse gas emissions and enhancing carbon sinks). It will aim to:

> …accelerate action … at different stages of the technology cycle, including research and development, demonstration, deployment, diffusion and transfer of technology … in support of action on mitigation and adaptation [30].

However, even if access to technology were greatly improved, other potential problems associated with the use of—especially hard—technology for climate adaptation remain. In addition to creating a false sense of security and the potential

Table 9.2 Examples of technologies to protect against, retreat from, or accommodate sea level rise and other coastal impacts of climate change.

Application	Technology
Protect	
Hard structural option	Dikes, levees, floodwalls
	Seawalls, revetments, bulkheads
	Groynes
	Detached breakwaters
	Floodgates and tidal barriers
	Saltwater intrusion barriers
Soft structural options	Periodic beach nourishment
	Dune restoration and creation
	Wetland restoration and creation
Indigenous options	Afforestation
	Coconut leaf walls
	Coconut fibre stone units
	Wooden walls
	Stone walls
(Managed) retreat	
Increasing or establishing setback zones	Limited technology required
Relocating threatened buildings	Various technologies
Phased-out or no development in exposed areas	Limited technology required
Presumed mobility, rolling easements	Limited technology required
Managed realignment	Various technologies, depending on location
Accommodate	
Emergency planning	Early-warning systems
	Evacuation systems
Hazard insurance	Limited technology required
Modification of land use and agricultural practice	Various technologies (e.g., aquaculture, saline-resistant crops), depending on location and purpose
Modification of building styles and codes	Various technologies
Strict regulation of hazard zones	Limited technology required
Improved drainage	Increased diameter of pipes
	Increased pump capacity
Desalination	Desalination plans

of lock-in (i.e., reducing future options), technologies tend to address the symptom rather than the cause of people's vulnerability (e.g., a focus on protection of exposed areas rather than considering retreat and resettlement). Increased deployment of hard technologies for adaptation might in fact worsen those problems if lessons from the past 15 years are not heeded.

The traditional view of climate adaptation to climate change, developed some 20 years ago, tends to assume that a national government is responsible for implementing technological adaptation measures (e.g., seeds, dams, irrigation schemes), which are selected on the basis of specific knowledge of future climate conditions [7]. This technology-based view of adaptation has been challenged, for three reasons [2, 6, 28].

First, even though climate science has made great advances over the past years, it is still often difficult to project future impacts of climate change in sufficient detail to justify investment in technological adaptation measures, in particular on a local scale. An important uncertainty relates to the effect of a changing climate on the frequency, magnitude and spatial occurrence of extreme weather events such as floods, cyclones, and droughts. Planning specific measures on the basis of projections of future climate conditions presents a great challenge, in particular for developing countries.

Second, technological adaptation measures can be important in reducing vulnerability to climate change, but they do have their limitations. Three issues need to be considered [19]:

- Technological adaptation measures may be only partially effective if they do not address non-climate factors that contribute to vulnerability to climate change. For example, the technological improvement of a water supply system to ensure the availability of water during dry spells will be of limited benefit to people who do not have access to this water. The inequitable distribution of water rights or the price of the water may be more important factors than deficient water supply technology in causing vulnerability to drought.
- Technological adaptation measures may be ineffective if they are not suited to local conditions. For example, new crop varieties may indeed be very resistant to an increase in salinity, but their acceptance in a community also depends on their costs and availability, farmers' access to fertilizer and other inputs, storage constraints, ease of preparation, flavour, and so on.
- Technological adaptation measures may turn out to be maladaptive (i.e., increase vulnerability) if they are implemented without recognition of relevant social and environmental processes. For example, new coastal infrastructure could disturb the offshore sediment balance, resulting in erosion in adjacent coastal areas. Irrigation can lead to the salinization of groundwater and the degradation of wetlands and can reduce subsistence farmers' access to groundwater and productive land.

Third, the traditional view of adaptation does not take into account the reliance of adaptation on development, and vice versa. People are vulnerable not only to climate change but also to a range of other stresses, depending on factors such as health status, education, and other socio-environmental circumstances shaped by political and economic processes [16, 24]. Government initiatives and technological measures designed to adapt to specific changes in climate may therefore fail to address the issues considered most urgent by local communities. These issues may include access to water and food, education, health, and sanitation concerns, as well as livelihood security.

The above analysis leads to the conclusion that a coastal adaptation strategy, in developed and developing countries alike, may need to include measures that address the underlying factors of vulnerability to climate change, particularly on a local scale. These underlying factors are typically structural issues characteristic of low development, such as high dependence on natural resources, resource degradation, inability to secure basic needs, and lack of information and capacity [29]. If technological measures are required as a means of reducing vulnerability to climate change, they need to be accompanied by non-technical measures (e.g., training and capacity building, institutional support) to ensure that the technologies are accessible, effective, and suited to local conditions.

9.4 Towards a Comprehensive Adaptation Strategy

The first empirical studies of climate adaptation (reviewed and assessed for the IPCC Fourth Assessment Report by Adger et al. [1]) have confirmed that the success of adaptation depends on broader development progress. When adaptation is limited to technological responses specific to climate change, it neglects the fact that vulnerability to climate change does not emerge in isolation. For example, it may be helpful to provide a rural household that grows a particular subsistence crop with a more salt-resistant variety, but a more robust and comprehensive adaptation strategy would seek to improve food security through a set of coordinated measures that include agricultural extension, crop diversification, integrated pest management, and rainwater harvesting. In addition, a poor rural household is more likely to use these options if it has a literate family member, access to investment capital through local financial institutions, can draw on relatively intact social networks, and hold policy makers accountable. In other words, it takes more than narrow, climate-focused measures to adapt successfully.

A recent study by McGray et al. [22] provides further confirmation. The study reviewed more than 100 initiatives in developing countries labelled as adaptation and found that—in practice—there was little difference between these initiatives and what can be considered good development. The difference lies more in the definition of the problem and the setting of priorities than in the implementation of solutions. The study presents adaptation as a continuum, ranging from more narrowly defined activities aimed specifically at dealing with the impacts of climate change to actions designed to build response capacity and address the drivers of vulnerability (see Fig. 9.1).

As the links between climate adaptation and human and economic development have become apparent, the term *mainstreaming* has emerged to describe the integration of policies and measures that address climate change into development planning and ongoing sectoral decision making. The benefit of mainstreaming would be to ensure the long-term sustainability of investments as well as to reduce the sensitivity of development activities to both today's and tomorrow's climate [3, 4, 12, 13, 19].

Mainstreaming is proposed as a way of making more efficient and effective use of financial and human resources than designing, implementing, and managing adaptation strategies separately from ongoing activities. Mainstreaming is based on

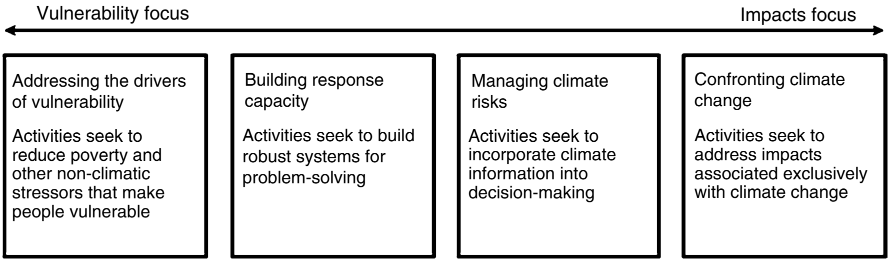

Fig. 9.1 Adaptation is a continuum from addressing the drivers of vulnerability to confronting the impacts of climate change [22]

the premise that human vulnerability to climate change is reduced not only when successful adaptation to the impacts takes place, but also when the living conditions for those experiencing the impacts are improved [12, 13]. Although mainstreaming is most often discussed with reference to developing countries, it is just as relevant to industrialized countries. In both cases it requires the integration of climate adaptation and sectoral and development policies. The institutional means by which such linking and integration is attempted or achieved vary from location to location, and from sector to sector, as well as across spatial scales.

Mainstreaming climate adaptation into development can mean different things to different people, depending on whether they hold a technology-based or a development-based view of adaptation. In the technology-based view, mainstreaming largely refers to ensuring that projections of climate change are considered in the decision making of relevant government departments and agencies, so that the technologies chosen are suited to the future climate. For example, in an area projected to experience more intense rainfall events, water managers would fit a drainage system with bigger pipes when replacing old ones, and agricultural extension services concerned about the possibility of increased drought would advise farmers to select crop varieties that are better suited to dry conditions. This type of mainstreaming has also been referred to as climate-proofing. It focuses on the two right-hand boxes in Fig. 9.1.

In the development-based view, adaptation to climate change is not restricted to such activities as installing bigger pipes and planting drought-resistant crops but instead takes a comprehensive approach that seeks synergies with development. Mainstreaming then means, in addition to climate-proofing, to ensure that development addresses non-climate issues that cause people to be vulnerable to climate impacts (e.g., securing equitable distribution of water rights to groups exposed to water scarcity). This type of mainstreaming considers the full continuum of Fig. 9.1. It recognizes that adaptation involves many actors, from individual households to national governments, but that an enabling environment must be created to ensure that these actors can adapt successfully and without creating conflicts over the use of resources. This approach includes removing existing financial, legal, institutional, and knowledge barriers to adaptation and strengthening the capacity of people and organizations to adapt.

When linking adaptation with development in developing countries, it is important to recognize that poverty reduction does not always mean reduction of vulnerability [2, 11]: in that case, synergies between adaptation and development may not exist. There are well documented instances of activities aimed at reducing poverty that have in fact increased vulnerability. For example, the conversion of mangrove forests into shrimp farms may generate economic gains but leaves coastal communities more vulnerable to coastal hazards such as storm surges. New roads in developing countries often affect settlement patterns; even if a new road is constructed so as to withstand climate change, it is equally important to consider whether it would attract new settlers to areas exposed to natural hazards.

9.5 Discussion and Conclusions

Since climate change was recognized as a global concern in the late 1980s, the major focus of decision makers has been on mitigation (i.e., reducing greenhouse gas emissions and enhancing carbon sinks) rather than adaptation. However, interest in adaptation to climate change has increased since the beginning of the century, because even the most radical mitigation efforts can no longer avoid at least some level of climate change, and impacts have become inevitable [25, 27].

In view of the fact that coastal areas are usually host to a range of sectoral activities, coastal technology and infrastructure to date has typically been designed to satisfy sectoral needs. With the additional challenge of climate change in coastal areas, the purpose and design of coastal technology and infrastructure may have to be revisited, or climate-proofed. However, this chapter has argued that climate-proofing alone may not suffice to reduce vulnerability to the impacts of climate change. Climate-proofing needs to be complemented with efforts to address non-climate factors that create low vulnerability in the first place. Without taking a broader, development-based view of adaptation, technology deployment may well be only partially effective at best, or even maladaptive. Technology can make an important contribution to climate adaptation in coastal areas, provided they are implemented in an enabling economic, institutional, legal, and socio-cultural environment.

The argument for mainstreaming climate adaptation into development is similar to the one used to promote integrated coastal management. More proactive and integrated planning and management of coastal areas has been widely suggested as an effective mechanism for strengthening sustainable development [8, 9]. The need to consider adaptation to climate change within the framework of integrated coastal management was discussed by WCC'93 [31] and Ehler et al. [10], among others. However, a recent assessment of integrated coastal management efforts by Billé [5] shows that the theory and rhetoric of the 1990s in part build on illusions that betray a lack of genuine understanding of the actors and actions involved. Progress in implementing integrated coastal management has therefore been slow.

Can a similar dichotomy between theory and practice be avoided for the mainstreaming of climate adaptation into development? There is no single magic formula for mainstreaming, but lessons can be learned from experiences in sustainable development, environmental policy integration, and integrated coastal management [26]. One basic lesson is that climate adaptation is not a one-off activity, but a participatory process. It comprises more than the deployment of some hardware; it also includes considering soft technologies and non-technological options to complement and facilitate the use of technology.

The key message of this chapter is that while technology can be very important in reducing vulnerability to climate change, its effectiveness depends on the economic, institutional, legal, and socio-cultural contexts in which it is deployed. Adaptation in coastal areas is therefore no longer the exclusive domain of engineers. If adaptation is to succeed and learn from past mistakes, the greatest challenges are now to be addressed by social scientists.

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Chapter 10
Uncertainties in the Cost-Benefit Analysis of Adaptation Measures, and Consequences for Decision Making

S. Hallegatte

Abstract In the early stages of rebuilding New Orleans, a decision has to be made on the level of flood protection the city should implement. Such decisions are usually based on cost-benefit analyses (CBAs). But in suchs an analysis, the results are contingent on a number of underlying assumptions and varying these assumptions can lead to different recommendations. Indeed, though a standard first-order analysis rules out Category 5 hurricane protection, taking into account climate change and other human-related disruptions of environment, second-order impacts of large-scale disasters, possible changes in the discount rate, risk aversion, and damage heterogeneity may make such hurricane protection a rational investment, even though countervailing risks and moral hazard issues reduce benefits. These results stress the high sensitivity of the CBA recommendation to several uncertain assumptions, highlight the importance of second-order costs and damage heterogeneity in welfare losses, and show how climate change creates an additional layer of uncertainty in infrastructure design that increases the probability of either under-adaptation (and increased risk) or over-adaptation (and sunk costs). In such a situation, alternative decision-making approaches

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should be favored. This paper suggests several strategies that are especially robust to uncertainty and that should be preferred in the current context of high uncertainty on future climate conditions.

10.1 Introduction

In most places, the natural risks have been managed in a very empirical manner. Past events and empirical evidence have been used to assess the level of risks and to estimate the need for protections like seawalls, dikes, and drainage systems. Today, there is a growing tendency to use economic analysis to manage risks and make decisions about protection investments. Considering their cost and the consequences of protection failure, it seems indeed reasonable to look for objective tools to guide and support policy making.

With climate change, moreover, natural risk management and adaptation have to be considered in an integrated and consistent framework. In particular, natural risks will evolve over time, and historical experience and empirical evidence will be less and less adequate [42], making it even more important to use models and quantitative techniques for decisions on risk management.

This paper starts by using the New Orleans case to illustrate how cost-benefit analysis (CBA) [4, 6, 26] can support this type of decision, and show what it can and what it cannot do. To do so, it focuses on the question of whether it is desirable to make the city flood protection system able to cope with Category 5 hurricanes. Since the aim is to illustrate a methodology, the present analysis will make some simplifying assumptions, to focus on what is most important.

In a CBA framework, New Orleans would only benefit from a flood protection system able to cope with Category 5 hurricanes, compared to a system able to cope with Category 3 or 4 hurricanes, if the additional cost of the upgraded protection is lower than the expected benefits from reduced flood damages. This is not certain to be the case, as surprising as this might appear given Katrina's devastating impact, and this article will show how two evaluations can reach opposite conclusions.

To do so, we will first carry out a simple CBA using available data on the damages caused by Katrina in New Orleans. As we will see, this first CBA clearly rules out a Category 5 protection system. Then, we will show how less optimistic assumptions about anthropogenic perturbations of the environment and consideration of additional processes—namely, second-order impacts, discount rate choice, countervailing risks and side effects, risk aversion, and damage heterogeneity—can change the terms of the analysis and thus potentially justify the implementation of a Category 5 system.

Considering this high uncertainty, which makes most decision-making methods difficult to use for the purpose of climate change adaptation, this paper concludes with proposals for alternatives. In particular, it suggests starting with an identification of strategies that are most able to cope with uncertainty.

10.2 Cost-Benefit Analysis for Adaptation and Risk Management

10.2.1 A First Cost-Benefit Assessment

To carry out a CBA of a Category 5 flood protection system in New Orleans, one needs to assess the cost, *C,* of such a system, and its expected benefits, *B*.

Assessing the cost, *C,* of an upgrade of the protection system is not easy, as it requires a precise definition of the system and an assessment of its construction and maintenance costs. In the very early stages of rebuilding New Orleans and its protection system, state officials estimated the cost of Category 5 protection between $2.5 and $32 billion [9, 51, 54]! More recent and detailed estimates by Louisiana Coastal Protection and Restoration (LACPR, led by the U.S. Army Corps of Engineers) reach even larger values. In the following discussion, and for illustrative purposes, it is assumed that the cost of Category 5 protection is $20 billion more than Category 4 protection.

Assessing expected benefits is even more problematic, as one needs to take into account benefits of various natures (e.g., avoidance of casualties, injuries, economic losses, psychological trauma) impacting different groups of people and possibly lying far in the future. This aggregation problem has been widely discussed (see, for instance, [1, 53] for aggregation issues between different categories of impacts and [48] for issues concerning intertemporal aggregation).

Regardless of these important problems, benefits can be defined as the net present value of the expected amount of damages avoided by the protection system upgrade. These benefits can, therefore, be calculated as the discounted sum, for each year from now through the lifetime of the protection system, of the annual probability that a Category 5 hurricane hits New Orleans multiplied by the difference between the damages of such a hurricane on a Category 4 versus a Category 5 protection system. This difference is discounted to take into account the fact that the same benefit is valued at a higher price when it occurs in the near future rather than further in the future.

The values of three parameters are thus necessary: the discount rate (δ), the probability of occurrence (p), and the amount of avoidable damages in the year n (d_n). From them, expected benefits, *B,* are easy to calculate[1]:

$$B = \sum_{0}^{T} P_n \left(\frac{1}{1+\delta}\right)^n d_n \qquad (10.1)$$

The variable T is the lifetime of the protection, and can be assumed almost infinite, provided that adequate maintenance is provided. Assuming that damages are

[1] It is assumed that protection systems have an infinite lifetime, after having checked that results were only weakly sensitive to the protection system lifetime, chosen in a reasonable range, for the selected values of the parameters. Indeed, as we will see, if $\delta \approx g$, where g is the economic growth rate (see below), the system lifetime becomes an important variable.

growing over time at the same rate as economic growth, g, which is a conservative hypothesis considering the current growth of economic losses due to natural disasters, expected benefits read:

$$B = \sum_{0}^{T} P_n \left(\frac{1}{1+\delta} \right)^n d_0 \left(1+g\right)^n \tag{10.2}$$

where d_0 is the amount of damages a flooding of New Orleans would cause today.

If the probability of landfall p_n is assumed constant and equal to p, then the equation can be simplified into:

$$B \approx \frac{pd_0}{\delta - g} \tag{10.3}$$

If the cost, C, of the flood protection system is lower than the expected benefits, B, then the system should be implemented. In spite of the difficulties already mentioned, a rough assessment of B can be made based on current information. From historical experience (i.e., by observing hurricane frequencies over the last century), one can evaluate the annual probability that a Category 5 hurricane hits New Orleans at about $p = 1/500$ (H. Saffir [54]).

The Office of Management and Budget (OMB), which carries out CBA of federal regulations in the U.S., uses two different discount rates to analyze policy decisions ([44]; see Appendix D, OMB Circular A-4). These two discount rates are used to assess the robustness of findings to the choice of discount rate and to capture two approaches to CBA. First, the discount rate can be calculated as the opportunity cost of capital, especially when strong capital reallocation is involved, yielding a value of 7% in the U.S. Second, especially when the project affects consumption patterns (e.g., fiscal changes), the discount rate can be calculated as the "social rate of pure preference" used by the average American saver in his saving decisions, yielding a value of 3%. Because the New Orleans flood protection system deals with the optimal allocation of capital, the use of the first value of 7% can appear *a priori* more appropriate. Note also that, according to the *Ramsey growth discount rule* [50], the discount rate can be evaluated by the relationship $\delta = \rho + \alpha\, g$, where ρ describes value judgments about time preferences and is referred to as the *rate of pure preference for the present;* α is the elasticity of the marginal utility and describes value judgments about the distribution of wealth; and g is the growth rate in the considered economy. The 7% discount rate used by the U.S. agency is consistent with a rate of pure preference for the present of $\rho = 4\%$ and an elasticity of the marginal utility of $\alpha = 1$, with an expected economic growth of the U.S. economy of $g = 3\%$. The 3% discount rate derived from the social rate of pure preference is consistent with a less optimistic prediction of economic growth, at 2%, and a pure preference for the present of $\rho = 1$. It is noteworthy that if damages are growing at the same rate as the economy, then a null pure preference for the present ($\rho = 0$) would imply that the flood protection would yield infinite benefit, provided that this flood protection system has a quasi-infinite lifetime.

Insurance and reinsurance companies (e.g., Munich Re, Swiss Re) and disaster modeling companies (e.g., RMS, EQECAT) estimate the direct damages due to any hurricane or flood, and their results are widely used as proxies for the overall economic cost of disasters. These companies estimate the cost of the New Orleans flooding at around $20 billion [52].[2] Taking into account casualties (about 1,000 people died in the flooding) raises the difficult issue of attributing a cost to a loss of life. Because the expression "*value of the human life*" problematically suggests a market in which one could buy or sell human lives, it is preferable to use the expression "*amount the public is willing to devote to reducing risk in order to save an additional life.*" Even though the value depends on the type of risk and the probability of occurrence of the considered event, most estimates lie between $1 million and $10 million in the U.S. We will use here the estimation of the U.S. EPA [61] of $5 million. Given this figure, the public would be willing to pay $5 billion to reduce risks in such a way that the equivalent of the human toll of the New Orleans flood is avoided.

To be complete, one has also to take into account the emergency costs, such as providing health care to hundreds of thousands of people and ensuring safety and security in the affected area. This cost has been estimated at around $8 billion after Katrina.

According to these rough estimates, $30 billion seems to be a good approximation of the cost of the New Orleans flooding.[3]

Assuming that a Category 4 protection system does not reduce the damages caused by Category 5 hurricanes, which is likely since there is little difference between no levees and broken levees, the expected present benefit of a Category 5 flood protection system in New Orleans can be calculated with Eq. 10.2 at $1.5 billion with a 7% discount rate and $6 billion with a 3% discount rate. Both are one order of magnitude lower than the cost of building such a system. This rough estimate clearly rules out an upgrade of the protection system to make it able to cope with Category 5 storms. It might be difficult to believe that the risk of a repetition of the devastation caused by the Category 4 hurricane Katrina is not enough to justify the implementation of the best possible protection system. However, our CBA suggests that it is more rational from an economic point of view to live the Katrina nightmare again in a more or less remote future.[4]

[2] Note that the losses due to the New Orleans flooding were only a fraction of the total cost of the Katrina landfall.

[3] In case of a repetition of the Katrina's scenario, a better evacuation would probably avoid a large part of the human losses and reduce this amount of damages. It has to be mentioned, however, (i) that Katrina's track forecasts have been very good and allowed for anticipated decisions before landfall, which is not always possible, and (ii) that an evacuation is always subject to organizational problems and unexpected practical difficulties, making the human part of the damages highly variable and uncertain.

[4] An annual probability of 1/500 means that there is a 20% chance of a Category 5 hurricane hitting New Orleans in the next 100 years, and a 33% chance in the next 200 years.

This estimate is, however, not very solidly grounded, as it does not take into account important processes whose impacts could be significant. In line with OMB requirements when uncertainty is large and economic implications are in excess of $1 billion [44], we will now review the parameters[5] of the CBA, and propose alternative estimates. We will not, however, attribute subjective probabilities to the various hypotheses that will be proposed and conduct a full probabilistic analysis, as can be found, for instance, for the climate change issue [40]. Indeed, current knowledge about natural disaster consequences seems still insufficient to assess these probabilities with any confidence, and the following sections will show how much research is still necessary.

10.2.2 Probability of Occurrence

In the first CBA, historical evidence was used to assess the probability of occurrence of a Category 5 hurricane landfall on New Orleans. This assessment cannot, however, be considered robust. Indeed, a flood protection system has a very long lifetime. Such a long lifetime arises, of course, from the long lifetime of infrastructures (dams, bridges, gates). But, above all, it comes from the fact that the flood protection system will shape the city development over an even longer time horizon. The decisions that are made on the city's protection will influence its vulnerability for at least this entire century. During this period, two mechanisms will influence hurricane risks, in addition to socioeconomic parameters like population change and asset vulnerability and value.

The first mechanism is soil subsidence, which is perturbed by human settlements and infrastructure [43]. The speed at which the soil, and therefore the levees, are subsiding is an important parameter determining the lifetime of a protection system and of the amount of potential damages. The second mechanism is climate, which will change in the course of the century, perturbed by the increasing amount of greenhouse gases in the atmosphere [59].

This climate change will influence hurricane risks through two channels: sea level rise and hurricane frequency and intensity. Indeed, a rising sea level makes the consequences of any storm surge more destructive, in the same way than soil subsidence does. Although sea level rise is very likely to be lower than 1 m at the end of this century, it is wise to consider the possible changes beyond 2100 and possible surprises in the pace of sea level rise. Sea level rise is driven by the thermal expansion of water, which can be predicted with relative certainty, and by the retreat of continental ice, which is more uncertain. In particular, the West Antarctic ice sheet and the Greenland ice sheet are susceptible of a more rapid melting than predicted and could increase sea level rise by up to 5 m over many centuries. Recent investigations

[5] Among the necessary assumptions in the CBA, it is often useful to distinguish between the political choices that must arise from a political process (e.g., discounting scheme), and the scientific uncertainties that can be —at least theoretically—solved through additional research (e.g., future probability of occurrence).

suggest, indeed, that the Greenland ice sheet is recessing much faster than expected, because of processes which are not taken into account by current models. The most pessimistic estimates of sea level rise in 2100 reach 1.4 m [49] or 2 m [46]. Large research efforts are currently underway to get a better understanding of these processes, but no definitive conclusion has been reached so far. Moreover, sea level rise and other human-induced disruptions to the Mississippi River delta (e.g., sediment deposition reduction) will worsen the floods associated with any hurricane falling on this low-lying area [8]. Thus, the probability of floods currently caused only by Category 5 hurricanes might increase, as less powerful hurricanes could also produce such devastating floods.

A second channel through which climate change modifies hurricane risks is, directly, through the probability of landfall. Indeed, it has been argued that changes in hurricane characteristics, due to climate change, are already observed: Webster et al. [62] observed that hurricanes in the strongest categories (4 and 5) have almost doubled in number and in proportion in 30 years; over the last 75 years, Emanuel [15] detected in the North Atlantic and western North Pacific basins a strong increase in the power-dissipation index (PDI), which is a proxy of the destructiveness of hurricanes. The debate on the significance and persistence of these trends, however, has yet to be resolved [16, 35]. The influence of climate change on hurricanes in the North Atlantic basin is a much debated topic and different approaches have predicted different futures. In Global Circulation Models (GCMs), hurricanes seem to be only marginally affected by higher temperatures [10]. But the low resolution of these models makes their findings on hurricanes very questionable. Downscaling approaches have logically been proposed: using a Regional Climate Model (RCM), Knutson and Tuleya [34] predict a significant increase in maximum surface wind speed (+6%); using its hurricane model, Emanuel [17] predicts that a (rather small) 10% increase in potential intensity, which is expected in the next decades, would cause a 65% increase in PDI and a 15% increase in maximum wind speeds. Hallegatte [28] shows that such a change would then translate into a 53% increase in the annual landfall probability of a hurricane over the U.S. coast, and a 215% increase for Category 5 hurricanes (see Fig. 10.1). And over the New Orleans region, representing 650 km of coast, the model's predictions are even more worrisome: the annual probability of landfall is found to be multiplied by 10 [28].

It is difficult to summarize all these results within a simple number. In the following, this paper will simply assume that climate change and subsidence may multiply by 5 the probability of the floods currently caused by Category 5 hurricanes, over the twenty-first century. This probability would thus increase to 1-out-of-100-years in 2100. This higher probability alone would make expected benefits from protection against Category 5 hurricanes rise from \$1.5 to \$2.4 billion or from \$6 to \$23 billion, depending on the discount rate (7% and 3%, respectively).

One can note that with an increasing landfall likelihood, the importance of the discount rate increases. This is not surprising: with increasing risks, most of the protection benefits occur in the far future, when hurricane risks are largest. Because the present value of these benefits is highly dependent on the discount rate, its importance rises.

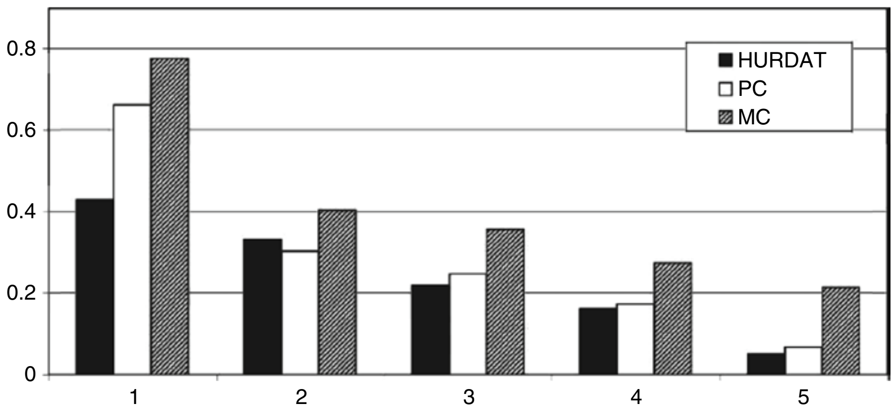

Fig. 10.1 Annual probability of hurricane landfall, for each category of the Saffir-Simpson scale, according to the data (*HURDAT*), in the present climate (*PC*), and in a modified climate (*MC*), because of climate change

These results suggest that climate change may have an important impact on long-term hurricane risk, even though changes in population and capital at risk will obviously be the main driver of vulnerability during the next decades. Additionally, the large uncertainty of the future probability of occurrence highlights one mechanism that has been disregarded in the climate change impact literature so far, but through which climate change might be responsible for significant economic damages in the future. Climate change increases the uncertainty of parameters that impact the design of long-term infrastructure, making them more likely to be ill-suited in the future climate. In the present case, the risk is either to face a series of avoidable disasters in New Orleans, if the probability of occurrence turns out to be much larger than predicted when the protection system is designed, or to bear the sunk costs of an expensive protection system based on an overestimated probability of occurrence.

10.2.3 Avoidable Damages

Another major difficulty remains in the assessment of the actual damages that could be avoided through an upgrade of the protection system. Assuming that New Orleans will be reconstructed and that all displaced households will return to their original city (we will address this issue later in the paper), the damages from the Katrina landfall can be used as a proxy for the damages a future flood may cause.

As mentioned earlier, however, several authors suggest that the direct costs, evaluated by insurance companies, may be poor proxies of overall costs, especially concerning large-scale events [7, 32, 33, 40, 57]. Indeed, direct cost can be amplified (i) by spatial or sectoral propagation into the rest of the economic system over the short term (e.g., through disruptions of lifeline services[6]) and over the longer term (e.g., sectoral inflation due to demand surge, energy costs, insurance company bankruptcy, larger public deficit, or housing prices that have second-order consequences on consumption); (ii) by responses to the shock (e.g., loss of confidence, change in expectations, indirect consequences of deepening inequality); (iii) by financial constraints impairing reconstruction (e.g., low-income families cannot rapidly finance the reconstruction of their homes); and (iv) by technical constraints slowing down reconstruction (e.g., availability of skilled workers, difficulties in equipment and material transportation, difficulties in accommodating workers). To measure the impact of these effects, Hallegatte et al. [28] and Hallegatte [29] introduced in economic models the role of the ability of the economy to fund and carry out reconstruction, and derived the *Economic Amplification Ratio* (EAR), which measures the ratio between the overall economic cost and direct loss due to a disaster. While this ratio is less than one for small-scale disasters, EAR is found to increase dramatically for large-scale disasters like the New Orleans floods. This increase arises mainly from the addition of the capital replacement cost of the production losses during the reconstruction phase. For example, if a $1 million plant was destroyed and immediately rebuilt, the loss would be $1 million; if its reconstruction is delayed by 1 year, the total loss is the sum of the replacement cost and of the value of 1 year of production. For housing, the destruction of a house with a 1-year delay in reconstruction has a total cost equal to the replacement cost of the house plus the value attributed to inhabiting the house during 1 year. The value of such production losses, in a broad sense, can be very high in some sectors, especially when basic needs are at stake (e.g., housing, health, employment).

Hallegatte [29] proposes a modeling of the economic consequences of Katrina using the ARIO model. This model provides the abilities of an IO framework to investigate indirect effects through demand, but it also (i) allows the assessment of supply side consequences, through the taking into account of forward and backward propagations of production limits within the economy; and (ii) avoids the excessive rigidity of a classical IO framework by allowing for substitution by importations when local production is perturbed. Also, a simple modeling of price response provides an estimate of price and profit responses in all sectors.

This analysis assumes that the total direct losses (insurable and uninsurable) from Katrina are $107 billion; i.e., much larger than the cost of New Orleans floods (about $30 billion), because of the effect of the wind and of impacts outside New Orleans. In terms of economic consequences, the orders of magnitude reproduced by the model in the Katrina case are realistic, with an instantaneous production reduction of 8% after the shock, and a production loss over the four last months

[6] For instance, Tierney [63] finds that data on the consequences of the 1993 Midwest floods and the 1994 Northridge earthquake suggest that "*business properties may escape direct damage and yet suffer extensive disruption as a result of lifeline service outages.*" These short-term costs, however, are usually included in insurance industry assessments as "business interruption" costs.

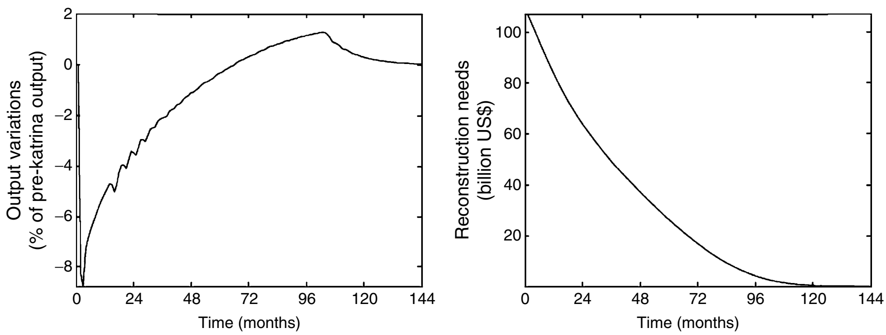

Fig. 10.2 Changes in Louisiana economy value-added due to the landfall of Katrina (*left-hand side*) and reconstruction needs (*right-hand side*). This figure shows that value-added reduction reaches 8% a few months after the shock, and lasts for several years; reconstruction is carried out over about 10 years

of 2005 of 2.8% of annual gross state product. This production loss underestimates the observed growth loss, which is close to 4.5% according to BEA data when exogenous growth is removed. Assuming that the economy will eventually return to its pre-disaster situation, the model predicts a reconstruction period of about 10 years.

The total loss of value added due to the disaster is equal to $23 billion, at pre-Katrina prices, for $107 billion of direct losses (see Fig. 10.2). Moreover, there is a loss in housing services, estimated at $19 billion. Since $107 billion of the remaining production is used for reconstruction purposes instead of normal consumption, total losses can be estimated at $149 billion. This increase represents a 39% increase compared with the direct cost, caused by economic mechanisms. This result emphasizes the difference between direct losses and total losses already mentioned [28]. Here the EAR, which measures the ratio of total losses to direct losses, is equal to 1.39.

Of course, social costs of large-scale disaster also involve other dimensions than direct economic losses and casualties, including psychological factors or political and social destabilization [38].

It is unclear what the EAR for the New Orleans floods only is, and it is likely that it is larger for the city flood consequences than for the entire Katrina consequences. In the following, given the great vulnerability of New Orleans and its vicinity (important economic activity in sensitive sectors like tourism, transportation, and energy production; low reconstruction capacity due to a large proportion of low-income population), the extent of the damages (80% of the city under water), and the difficulties currently met in the reconstruction process, a conservative estimate of the actual overall cost of the New Orleans floods is at least double the insurers' approximation based on direct losses only; that is, $60 billion.

Using the new values of event probability and potential damages, the expected benefit of an upgraded protection system would be $4.8 billion with a 7% discount rate and $46 billion with a 3% discount rate.

10.2.4 The Resettlement Issue

We assumed in the previous section that New Orleans will be rebuilt with the same structure it had before Katrina and that all previous inhabitants of New Orleans will return to the city, even if no improvement of the flood protection system is undertaken. This assumption is at odds with what is observed: while the population in the Orleans-Metairie-Kenner Metropolitan area was estimated by the Census Bureau at 1,313,460 in July 2005, it was estimated at only 1,189,981 in July 2009 (with a low at 987,535 in July 2006). If this lower population level is maintained, the costs of a new flood would of course be reduced compared with the 2005 one, making our assessment of avoidable damages overestimated. But it must be remembered that the flood protection system, the design of which is currently being discussed, will protect New Orleans for at least one century. The pertinent variable is thus the population over the long term, not over the next decade. And the observed low repopulation rate is partly explained by the slow reconstruction pace due to short-term constraints, consistent with Hallegatte [29] and Fig. 10.2. It provides, therefore, no estimate of the long-term repopulation of the city.

To assess the long-term repopulation, we assume that, before Katrina, the risk of hurricane was perfectly known and that the New Orleans inhabitants exhibited rational behavior. We neglect here the potentially important role of social networks [41]. Within this framework, the large population of New Orleans before the storm can only be explained by comparative advantages of the city's location in some sectors (e.g., tourism, shipping) and by the households' willingness-to-pay (WTP) to live there, because of environmental amenities. Both should have more than compensated the well-known hurricane and flood risk, even in absence of an improved flood protection system. If these comparative advantages and this WTP have not been changed by Katrina, and if basic services, infrastructures and social networks can be restored, these assumptions mean that the New Orleans population could eventually return to its pre-Katrina level, even in absence of improved flood protection. They also suggest that the currently observed population reduction is more related to financial and technical constraints than to voluntary choices.

These assumptions, while debatable, can explain the pre-storm New Orleans and allow us to separate the design of the flood protection system from the reconstruction issue and to justify the use of the 2005 flood data to estimate the cost of a future flood.

10.2.5 Countervailing Risks and Side Effects

Unfortunately, it is also necessary to take into account the possible side effects implied by the implementation of a large-scale protection system. These side effects can yield ancillary benefits like infrastructure improvement, as mentioned by Allenby and Fink [2], or create or increase other risks, referred to as *countervailing risks*[7] by Wiener [64], who calls for a broader accounting of them in risk management.

One cannot assess a flood protection system without taking into account moral hazard and equity issues. A flood protection system funded through nationwide taxes, like a uniform insurance premium, can constitute an incentive for people to settle in at-risk areas, as they do not pay for the risk their location choice creates. Indeed, even if they prefer to live in New Orleans rather than anywhere else, it is likely that fewer people will resettle in New Orleans if they think the Katrina catastrophe can happen again than if a flood protection system makes the probability of such an event negligible. This mechanism is potentially significant, since the large increases in population and investments in hurricane-prone regions are responsible for most of the explosive trend in hurricane damages observed over the last decades [47]. It should be noticed, however, that the urbanization of vulnerable areas around New Orleans in the past few decades does not seem to have been driven mainly by an over-protection against hurricane floods, but rather by the tradeoff carried out by low-income households, who have high rates of preference for the present and poor access to information, between long-term flooding risks and immediate lower housing prices.

These side effects, however, create a paradox. We would expect an increase in the system benefits from the fact that the protection system would allow a larger number of households to resettle in New Orleans, where they prefer to live. It is not the case. Instead, it reduces the benefits, by lowering the number of persons at risk if the protection system is not built. This paradox arises from the fact that, again, we do not take into account the comparative advantages of New Orleans and the welfare gain or loss (or WTP) of households who would like to live in this city if they were protected from floods. This paradox suggests that a CBA analysis of the flood protection system taking into account countervailing risks cannot be carried out in a rigorous manner independently of a modeling of individual location choices. Such a modeling, however, is made very difficult by the uncertainty of household WTP, and we will have to rely on other approximations to take into account countervailing risks in our analysis.

The importance of these side effects will be heavily dependent on the design and practical implementation of the protection system. In particular, huge negative consequences would certainly result from the implementation of an ambitious flood protection system that is not carefully maintained over the long term. In this worst case scenario, the existence of the protection system would raise investment and population in the so-called protected area, which would not be protected any more after a few decades of negligence, making s even larger than if no protection was implemented in the first place. As a consequence, the implementation of a protection system must be considered a long-term commitment.

[7] Examples of such countervailing risks in flood management are provided by Glenn et al. [19] or Christensen [11].

Also, avoiding negative outcomes from the future flood protection system requires careful design and implementation, in order to protect already urbanized areas without steering additional urbanization toward unprotected flood-prone locations. In this respect, the future flood protection system in New Orleans is certainly not only a system of dams, bridges, and gates. It should also include an important set of new regulations for future urban development. A wisely designed flood protection system should protect selected areas with dams and levees, and ensure, through land-use regulations, that investments are not attracted to unprotected areas. Hopefully, increased experience with flood management and the high visibility of the project will foster a flood protection plan that limits the negative effects and promotes positive ones, making the overall consequences of these side effects positive or, if this proves impossible, negligible compared with direct costs and benefits.

To be conservative, however, we will take into account the fact that a flood protection system could increase the population and capital at risk compared with an optimal situation. To do so, we will assume that, if no protection system is implemented, the potential damages growth rate will be lower than nationwide economic growth, by an amount $\Delta g = 0.5\%$, because of the influence of hurricane risks on housing and investment location choices.[8] We will neglect the fact that, if the protection system is not implemented, there is a loss of welfare for households who would move to New Orleans if the city were protected from flood but who do not move because of the absence of such protection.

It means that Eq. 10.2 is changed into:

$$B = \sum_{0}^{T} P_n \left(\frac{1}{1+\delta} \right)^n d_0 \left(1 + g - \Delta g \right)^n \tag{10.4}$$

With this new equation, the expected benefit of an upgraded protection system would be \$4.2 billion with a 7% discount rate and \$27 billion with a 3% discount rate. This result shows the importance of assumptions about how the protection (and absence of protection) influences the development of the region, which can easily reverse what appears the reasonable decision.

10.2.6 Choice of the Discount Rate

As already mentioned, the CBA of a flood protection system has to deal with very long time horizons, making the value of the discount rate controversial. Indeed, there are intense debates [48, 58] about the discount rate that should be used for

[8] In other terms, the existence of the protection system is assumed to increase economic growth in the protected area by 0.5% per year, making it equal to nationwide economic growth.

environmental or long-term issues that involve intergenerational issues. When intergenerational equity is strongly involved, OMB suggests that discount rates between 1% and 3% are appropriate, since the welfare of next generations should not be discounted and only the fact that they are likely to enjoy higher consumption levels should be taken into account. Hallegatte [30] proposes a decreasing intergenerational discount scheme to avoid favoring current generation at the social scale while taking into account the observed preference of the present of individuals. Some governments (e.g., U.K.) favor a decreasing discount rate over time, justified by the uncertainty over future economic situations [20, 45, 60, 63].

Clearly, as illustrated by our comparison of 3% and 7% discount rates, the influence of this political choice is very great. In other terms, decision making concerning protections against very infrequent events is highly dependent on the weight attributed to the well-being of future generations.

10.2.7 Risk Aversion and Damage Heterogeneity

A society that would use the previous method to assess a protection system is called *risk-neutral*. A risk-neutral agent is indifferent to risk; i.e., it does not see any difference between losing $1 with certainty and having a 10% chance of losing $10, because the expected loss is the same in both cases. Theoretically, such an agent would never pay for insurance. Regarding protection against large-scale floods, however, there are good reasons to justify *risk-averse* behavior: people might indeed prefer to pay an additional amount of money (a *risk premium*) to avoid the risk of costly and deadly floods.

To incorporate risk aversion, it is possible to change the assessment framework and use a *utility function* that measures the welfare gain or loss that is associated with any financial gain or loss. A utility function with risk aversion assumes that the increase in utility due to a $1 gain is smaller—in absolute value—than the decrease in utility due to a $1 loss. As a consequence, the risk of gaining or losing $1 with equal probability lowers the expected utility and is, therefore, equivalent to a certain financial loss, which is referred to as the *risk premium* or the *equivalent-certain* outcome.

However, if we assume that the damages due to a hurricane landfall are perfectly shared among the whole population of the U.S., the damage per capita is small (a few 100 U.S.$ per capita). In such a situation, the Arrow-Lind theorem [5] demonstrates formally why risk-aversion can be neglected, supporting the choice of the states that consider self-insurance as a basic principle (e.g., France). Indeed, using a utility function with a constant relative risk aversion of one, as suggested in Arrow [3] for households in developed countries, the risk-premium is negligible.

The picture is different, however, if a substantial part of the damages impacts only a small fraction of the population. Indeed, when the utility function is not linear, the utility derived from the consumption of $1 becomes lower as consumption increases. This effect represents the fact that rich people do not gain as much from the consumption of $1 as poor people do. But, it also means that it is not equivalent for a group of ten people to lose $1 each and to know that one of them will lose $10. The consequences of these factors on the CBA analysis of a hurricane landfall can be very significant. In this case, indeed, individual losses become significant (as large as 90% of annual consumption for the affected population) and risk aversion appears far from negligible. This effect would even be amplified because (i) low-income people are more likely to belong to the affected population [38], accounting for pre-existing income inequalities would increase utility losses; and (ii) the actual reparation of damages is even more unequal than we assumed, as a few people usually suffer from most of the losses (house, belongings, life environment, and also friends and relatives). Regardless, neglecting the damage heterogeneity in the CBA leads to a large underestimation of the benefits from an improved protection system.

10.3 Conclusion for Decision Making

Building a flood protection system able to cope with a Category 5 hurricane in New Orleans is a huge investment, and it is wise to precisely assess its benefits before any implementation decision, as other, less costly, projects might be more efficient to improve the population's well-being.[9] One must, however, be very careful of the underlying assumptions used in the benefit assessment. Indeed, using probabilities derived from historical experience and direct cost estimates produced by insurance companies lead to low assessments of benefits and rule out any additional flood protection system. Nonetheless, making less optimistic assumptions about possible anthropogenic increases in flood probabilities and taking into account estimates of second-order disaster costs, public risk-aversion, and damage heterogeneity can reverse the conclusion of the CBA.

These results suggest that a CBA is useful but should encompass the whole set of possible assumptions to check its robustness. These results show that CBA reaches very different results for reasonable parameter values and therefore can rarely be used to make a decision in an objective way. It is crucial to note that result uncertainty does not arise only from scientific uncertainty (e.g., on climate sensitivity or building vulnerability) that could be reduced with more research. Most of it arises from value judgements on which consensus exists or is likely to exist in the future.

Since uncertainty is very large and ethics considerations are important, risk management decisions will remain political ones. CBA, however, can be used to help organize the debate, by linking the different opinions of various groups on what should be done to different opinions about the parameters of the analysis (e.g., the discount rate, or the amount of avoidable losses). CBA should therefore be understood as a complement and a tool to open consultations and discussions, not as a replacement for them.

[9] This is especially true if improved track forecasts, warning systems, and evacuation plans can avoid human losses at low cost.

The great influence of assumptions about climate change is a new and important difficulty, considering the great uncertainty of future climate change, at global scale as well as local scale [13, 14, 27, 31]. New decision-making methods are necessary to include this new uncertainty, which in most cases cannot be expressed using probabilities. Alternative decision-making methods have been proposed, including the precautionary principle [21, 56], robust decision making [36, 37], focusing on flexibility and reversibility [18, 22, 31], or option-values and sequential decision making [25].

One can start with an identification of options and measures that are most adapted to the current situation of high uncertainty. Some of them are listed in the following section, with a few illustrations. This list does not pretend to be exhaustive, but suggests ideas for more robust strategies.

10.3.1 No-Regret Strategies

"No-regret" measures constitute a first category of strategies that are able to cope with climate uncertainty. These strategies yield benefits even in absence of climate change. For example, controlling leakages in water pipes is almost always considered a very good investment from a cost-benefit analysis point-of-view, even in the absence of climate change. On the other hand, additional irrigation infrastructure is an interesting measure in some regions in the current climate. In others, considering the high investment costs necessary, it would be beneficial only if climate change decreases precipitation. So, irrigation is a no-regret strategy only in some regions.

Improving building insulation norms and climate-proofing new buildings is another typical example of no-regret strategy, since this action increases climate robustness while energy savings can often pay back the additional cost in only a few years. Considering its high cost, on the other hand, it is unlikely that the climate-proofing of existing buildings is no-regret. Land-use policies that aim at limiting urbanization and development in certain flood-prone areas (e.g., coastal zones in Louisiana or Florida) would reduce disaster losses in the present climate, and climate change may only make them more desirable. Also, in many locations, especially coastal cities, building sea walls would be economically justified by storm surge risks with the current sea level [43], and sea level rise will only make these walls more socially beneficial.

This idea is therefore not to design adaptation strategies assuming that the present situation is optimal and should be preserved in spite of climate change. Instead, the identification of sub-optimalities in the current situation may help identify adaptation options that are beneficial over the short term (i.e., easier to implement from a political point of view) and efficient to reduce long-term climate vulnerability.

It would be interesting to know why these no-regret actions are not implemented yet. Many obstacles explain the current situation, including (i) financial and technology constraints, especially in poor countries; (ii) lack of information and transaction costs at the micro-level; and (iii) institutional and legal constraints.

While the first two issues are well identified, more research is needed to understand the latter. For instance, what explains the difference in risk management between the Netherlands, where flood risks are seriously investigated and managed, and Louisiana, where flood defenses have been neglected for decades? Detailed case studies should be able to answer such question and propose “best practices” that could be generalized. In many locations, the implementation of these practices would constitute a very efficient first step in a long-term adaptation strategy.

10.3.2 Reversible Strategies

Second, it is wise to favor strategies that are reversible and flexible over irreversible choices. The aim is to keep as low as possible the cost of being wrong about future climate change. Among these examples, one can mention “easy-to-retrofit” defenses; i.e., defenses initially designed to allow for cheap upgrades if sea level rise makes them insufficient; the climate proofing of new buildings and infrastructure, which has an immediate cost but can be stopped instantaneously if new information shows that this measure is finally unnecessary; and insurance and early warning systems that can be adjusted every year in response to the arrival of new information. Another example is restrictive urban planning. When deciding whether to allow the urbanization of an area potentially at risk of flooding if climate change increases river runoff, the decision-maker must be aware of the fact that one answer is reversible while the other is not. Refusing to urbanize, indeed, has a well known short-term cost, but if new information shows in the future that the area is safe, urbanization can be allowed virtually overnight. This option, therefore, is highly reversible, even though it is not costless since it may prevent profitable investments from being realized. Allowing urbanization now, on the other hand, yields short-term benefits, but if the area is found dangerous in the future, the choice will be between retreat and protection. But retreat is very difficult politically, especially if urbanization has been explicitly allowed. Protection is also expensive, and it is important to consider the residual risk: protection is efficient up to the protection design. If the protection is overtopped or fails, human and economic losses can be very large. So, allowing urbanization is very difficult to reverse, and this strategy is highly vulnerable to the underestimation of future risks. Of course, it does not mean that urbanization should always be rejected. It only means that, in the decision-making process, the value of the reversibility of a strategy, often referred to as the “option value,” should be taken into account.

The option value is often used to assess the possibility of delaying a decision [25], as in this urbanization example. For many infrastructure decisions, however, waiting is not an option, since all climate-sensitive decisions (e.g., in water management or housing) cannot simply be delayed by decades. The valuation of reversibility, through the option value concept or through multi-criteria decision-making frameworks, have thus to be applied to the comparison of adaptation strategies with different “irreversibility levels.”

10.3.3 Safety-Margin Strategies

Third, there are "safety margin" strategies that reduce vulnerability at negative, null, or negligible cost. The existence of such strategies to manage sea level rise or water investments has been mentioned by Nicholls and Leatherman [23, 24, 43]. And there are practical applications today. For instance, to calibrate drainage infrastructure, water managers in Copenhagen now use runoff figures that are 70% larger than their current level. Some of this increase is meant to deal with population growth and the rest is to cope with climate change, which may lead to an increase in heavy precipitation over Denmark. This 70% increase has not been precisely calibrated, because such a calibration is made impossible by climate change uncertainty. But this increase is thought to be large enough to cope with almost any possible climate change during this century, considering the information provided by all climate models. This move is justified by the fact that, in the design phase, it is inexpensive to implement a drainage system able to cope with increased precipitation. On the other hand, modifying the system after it has been built is difficult and expensive. It is wise, therefore, to be over-pessimistic in the design phase. The same is often true for dikes and sea walls: construction costs alone are often manageable (see, e.g., The Foresight report on Flood and Coastal Defences, Volume 2, Table 5.2., available on http://www.foresight.gov.uk); a significant fraction of the total social cost of a dike arising from amenity costs (e.g., loss of sea view), and other indirect effects (e.g., loss of biodiversity, other environmental costs on ecosystems, or enhanced erosion in neighboring locations). As a consequence, the marginal cost to build a higher dam is small compared to its total cost. If a dike has to be built today to cope with current storm surge risks, therefore, it may be justified to build it higher, in such a way that it can cope with future sea levels.

Often, when it is cheap, it is sensible to add "security margins" to design criteria, in order to improve the resilience of infrastructure to future (expected or unexpected) changes. Cheap safety margins can be introduced in many existing adaptation options, to take into account climate uncertainty: developing drainage infrastructures in developing country cities can be considered as an adaptation measure; making these drainage infrastructures able to cope with more water than we currently expect is a "safety-margin" strategy that makes this adaptation measure more robust.

The existence of cheap safety margins is especially important for adaptation measures that are not reversible or flexible. The options that are irreversible (e.g., retreat from coastal areas) and in which no cheap safety margins are available are particularly inadequate in the current context. The options that are irreversible but in which safety margins can be introduced (e.g., coastal defenses or improvement of urban water-management infrastructures) can be implemented, but only with a careful taking into account of future climate change scenarios.

10.3.4 Soft Strategies

Fourth, technical solutions are not the only way of adapting to changing climates. Sometimes, institutional or financial tools can also be efficient. For instance, the institutionalization of a long-term planning horizon may help anticipate problems and implement adequate responses: in the framework of the California Water Plan, all water suppliers that provide water to more than 3,000 customers in California have to carry out, every 5 years, a 25-year prospective of their activity, including the anticipation of future water demand, future water supply sources, and “worst-case” drought scenarios. These kinds of exercises are very useful because they force planners to think several decades ahead, they create contacts between economic agents and climate scientists, and they help shape strategies to cope with future changes. In the present situation, where parameters that used to be known become uncertain, a long-term planning horizon is key to determining where and how to change business practices.

Institutional solutions have also an important role to play in coastal zone management: while managing coastal floods did not require regular updates in a world with an almost constant sea level, climate change and sea level rise will make it necessary to analyze coastal flood risks on a regular basis and to implement upgrades when required. The creation of specific institutions to carry out these analyses may, therefore, be an efficient adaptation option. For instance, the Netherlands went through a large flood in 1953, which caused more than 1,800 deaths and extensive damages. The response to this event was not only an engineering response: a commission, the Delta committee, was created to manage the response from an institutional and technical point of view. This committee published in 1960 the Delta Plan, which included an engineering part, the Delta Works. But the Delta committee also introduced a completely new approach to determine the required level of protection against flooding. Using cost-benefit analyses, the Delta committee determined an acceptable level of flood risk and, from it, derived an optimum level of protection, formulated as return period for the design water level. The Dutch Law on Water Defences also requires that water levels and wave heights used in risk analyses and in the design of protections should be updated every 5 years and that water defenses should be evaluated for these new conditions. Of course, this response did not lead to the disappearance of the risk, and the Netherlands were flooded again in the 1990s from river flood, which had been underestimated. Nonetheless, risk management in the Netherlands appears extremely efficient and well designed to cope with changing risks like climate change (and also subsidence and other risk drivers).

In the same way, in hurricane-prone regions, it may be more efficient to implement an efficient warning and evacuation system combined with a strong (possibly expensive) insurance scheme and recovery plan than to protect all populations with seawalls and dikes. In the former case, the population is evacuated in dangerous conditions (e.g., an approaching hurricane) to avoid deaths and casualties, and material losses are paid by insurance claims, so that recovery and reconstruction are as effective as possible. The insurance premium the population will have to pay to live in this at-risk area may be large, but remains lower than the cost of protecting the areas with dikes. Of course, warning systems are not flawless and it is always difficult to decide whether and when to evacuate, but the Katrina experience demonstrated that hard protection can also fail, with the most tragic consequences.

Soft adaptation options are also reversible solutions. The key advantage of soft adaptation options, indeed, is that they entail much less inertia and irreversibility than hard adaptation: an insurance scheme can be adjusted every year, unlike a water reservoir. The risk of sunk costs if climate projections are wrong is much lower for institutional and financial strategies than for technical adaptation projects, which makes them more suitable to the current context of high uncertainty.

Soft options like land-use plans, insurance schemes, and early warning systems will have an influence on business investment choices and household decisions and, therefore, on hard investments. For instance, land-use planning restrictions can be seen as soft options, but their consequences in terms of construction make such a qualification questionable. As a consequence, no option is purely a soft option.

10.3.5 Strategies That Reduce Decision-Making Time Horizons

Fifth, the uncertainty regarding future climate conditions increases rapidly with time. Reducing the lifetime of investments, therefore, is an option to reduce uncertainty and corresponding costs. This strategy has already been implemented in the forestry sector by choosing species that have a shorter rotation time. Since species choice cannot be made reversible and no safety margins are available in this sector, this option is interesting in spite of its cost. In other sectors, it is also often possible to avoid long-term commitment and choose shorter-lived decisions. For example, if houses will be built in an area that may become at risk of flooding if precipitation increases, it may be rational to build cheaper houses with a shorter lifetime instead of high-quality houses meant to last 100 years.

10.3.6 Taking into Account Conflicts and Synergies

A last point deserves to be mentioned. Adaptation strategies often have side effects that can be either negative or positive. For instance, in the case of coastal infrastructure to protect against storm surge such as sea walls, these may threaten the tourism industry because they change landscape, ecosystem health, and beach leisure attractions. Coastal attractiveness for leisure and tourism activities is closely linked to various parameters such as landscapes [39], the quality of the environment, and water availability. As a consequence, in some contexts, hard protection would simply not be an option. Equally important, hard protection could contribute to fish stock depletion by further damaging coastal ecosystems [12]. Since 90% of fishes depend on coastal zones at one point in their life cycle [55], such impacts could have a significant impact on economic income from fisheries. Taking into account environmental costs on ecosystems is thus essential.

There are also conflicts between adaptation options. For instance, an increased use of snow-making to compensate for shorter skiing seasons in mountain areas would have negative consequences for water availability and—for example—agriculture. This example shows that adaptation strategies that look profitable when considering only one sector may be suboptimal at the macroeconomic scale because of negative externalities. As a consequence, public authorities will have to be aware of this risk and monitor the emergence of new externalities from adaptation behaviors.

Adaptation also interacts with mitigation policies. For example, improved building norms would lead to large ancillary benefits in terms of energy consumption and reduced greenhouse gas emissions. And indeed, the benefits in terms of emission reduction of several adaptation options can make these measures interesting, even when they imply some irreversibility. But conflicts may also appear between adaptation and mitigation measures. Many adaptation strategies that are appealing today imply increased energy consumption, like a generalization of air conditioning. In the design of adaptation strategies, therefore, future energy costs have to be taken into account: if there is a high carbon price in 2030, desalinization plants using fossil fuels may become excessively expensive to run. Considering the huge investment cost of these plants, this possibility has to be accounted for in the decision-making process. Moreover, there is an unfortunate correlation between energy costs and climate change impacts. If climate change and its impacts appear to be worse than expected in 50 years, stricter mitigation strategies are likely to be introduced, making energy costs and carbon prices rise. Highly energy-consuming adaptation options, therefore, seem to be particularly non-robust to unexpected climate-related changes.

Finally, there are conflicts between adaptation strategies and other policy goals, and no strategy can be implemented if these conflicts are not acknowledged. Building norms can be modified to make buildings more resilient to heat waves, but this would raise construction costs, which may be a problem in countries or regions with housing scarcity (e.g., Paris and its region). Also, different building norms, and building retrofitting for higher temperatures, would modify the external aspects of buildings and cities. This move could therefore be opposed on the ground of patrimonial protection: does the population want to keep an historical neighborhood as it is, or to change it to improve comfort and living conditions? Solving these debates often requires going beyond a top-down approach in which adaptation strategies are developed by experts on the basis of scientific information. Participatory approaches, in particular, help identify which strategies are consistent with the local context and goals, and select no-regret strategies that answer other demands from the population.

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Chapter 11
Sustainable Development and Climate Change Challenges

Case of a Public Organization

M. Merad, N. Dechy, and F. Marcel

Abstract In 2007, the French government organized a set of meetings around environment and sustainable development problematics called, "Environment Grenelle". The conclusions of these meetings were introduced in a new law published in August 2009 ("Grenelle 1," n 2009-967). In Article 1 of this law, the State is obliged to frame a Sustainable Development National Strategy (SDNS) structured around nine challenges. The first challenge consists in fighting against climate change. The SDNS is used as a plinth for the involvement of public and private organizations in this perspective.

Many practical questions are raised when struggling against climate change and implementing the sustainable development principle (SD Principle) within the organizational framework: How to develop adaptive methods and tools helping organizations reach a new balance facing environmental, economic, and social risks induced by those broad challenges? Are there any standards of reference and if not can we develop an innovative approach to support decision making within uncertainty? How to develop a dashboard to a proportioned allocation of resources adapted to the various stakeholders and level of decision within the organization? How to compare actions that can have different impacts in different subsystems and with different time frameworks?

After a brief historical overview of the origin of the challenges of sustainable development and climate change, we will raise briefly, in the first part of the paper, some theoretical issues and discuss why struggling against such a global issue as climate change is a complex problem within an organization and how sustainable

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development principles can support decision making under uncertainty. In the second part, we will address practical issues for an organization facing the challenges of sustainable development and climate change. Indeed, we will relate the experience of framing a sustainable development plan within a public institution using an organizational approach and a multiple-criteria decision aid methodology. Finally, we will discuss the decision makers' choices and the lessons learned by implementing an innovative approach that we set up to face these new challenges.

11.1 Introduction and Historical Context

11.1.1 Climate Change as a Catalyst for Sustainable Development

The impact on environment of industries' and cities' development raised step by step the question of sustainability.

First of all, environmental concerns are not really new in many countries and have long been regulated. For instance in France, the Decree of October the 15th in 1810, at the time of Napoléon, regulated manufacturing activities and workshops that were unhealthy, polluting, or hazardous. Large steps were taken in the decades after World War II, when environmental and risk regulations were passed (e.g., to control industrial sites with Decree 53–578 in 1953 for the *nomenclature,* or listing of potential polluting and hazardous sites). Such issues are now regulated within the EU by the Seveso II and IPPC (Integrated Pollution Prevention Control) directives. In France, a state secretary and Ministry for environment have existed since the early 1970s. Their labeling changed and integrated the words *ecology* and *sustainable development* in 2002. Thus, from a historical point of view, environmental concerns are at the origin of the sustainable development issue.

Since the Rio conference on 1992, France, like other countries, has become more and more aware of sustainable development stakes when defining policies. It took a few more years for the French government to adopt a National Strategy of Sustainable Development (NSSD) for the period 2003–2008 based on the European strategy on sustainable development adopted by the European Council of Goteborg in 2001 and the growth and employment strategy decided in Lisbon in 2000.

More recently, a cultural shift was observed with the rising concerns about climate change monitored by the *Groupe International d'Experts sur le Climat* (GIEC) since 1988. Under the umbrella of the UN, the discussions about greenhouse gases were initiated and the Kyoto Protocol was voted on in 1997. Later, closer to the 2005 implementation year, some politicians, such as Al Gore, amplified the alert and managed to mobilize international public opinion for a struggle against climate change risks (e.g., until the 2009 Copenhagen conference failure). It is noteworthy that the mobilization for fighting against climate change has been the main catalyst to make sustainable development a top priority for many countries.

In France, it was particularly obvious during the presidential election campaign in 2006 and 2007. However, in this period climate change almost overwhelmed the systemic change issues advocated by the sustainable development proposal. Climate change introduces a new weight of energetic dimension and efficiency to sustainable development. It is not obvious now whether the negative impacts of the present financial systemic crisis will accelerate or delay the global transition towards a more sustainable development model.

11.1.2 Implementation Framework for Sustainable Development and Climate Change Struggle

These historical trends are shaping the conditions in which the regulatory and implementation framework are designed to cope with sustainable development and climate change challenges. Another key influence on climate change risk management is the promulgation of the Aarhus Convention signed in 1998, about the rights of citizens to be informed. This convention invites countries to reconsider the social dimension by improving transparency in the development of environmental regulations, promoting governance and participative approaches.

In France, as a result of the presidential election, different institutional workshops named *"Grenelle de l'Environnement"* were launched in 2007. These workshops offered a participative framework for the stakeholders and citizens and have ended by fixing a legislative structure, "Grenelle 1 Law of August the 3rd, 2009," to the dynamic initiated by the 2009–2013 NSSD. Article 1 of the Grenelle 1 law specifies that the law will fix a framework to fight against and adapt to climate change, preserve biodiversity, contribute to an environment that respects health, and preserve the landscape. The fight against climate change is the first challenge of this law and was fixed as a priority for public and private organizations. For that purpose, organizations were asked to frame a Sustainable Development Plan (SDP). For semantic reasons, in private organizations this plan is referred to as "Corporate Societal Responsibility" (CSR). In public organizations, this plan is referred to as "Organization Societal Responsibility" (OSR) or "Exemplary Administration Plan" (EAP).

Each year, state services and public organizations must present and demonstrate their efforts to reach the Grenelle 1 challenges. More specifically, the French Ministry of Environment published in 2008 a "sustainable development charter" that commits the public signatory organizations to: (i) organize strategic thoughts and discussions around the Sustainable Development Principle (SD Principle); (ii) render these discussions in the organization's strategy, projects, and management practices; (iii) frame a strategic document describing how the organization copes with both social and environmental concerns in its annual report; and (iv) frame a sustainable development action plan that considers the governance aspects identified below.

11.2 Climate Change and Sustainable Development

11.2.1 Why Fighting Against Climate Change Is a Complex Problem Within an Organization

The links between implementation of the SD Principle within organizations and the impact of climate change raise the theoretical question of the impact of local actions on the global system. In fact, the interactions between these actions and the global system are complex and deductive methodological approaches cannot be used.

Indeed, the deductive approach presupposes that the behavior of the global system can be deduced and understood by understanding the behavior of its subsystems. Thus, this approach based on an *analytical* process aims at highlighting the potentialities of evolution of the subsystems, taking into account their current state [6] and can only be applicable while fulfilling the requirements of the *applied sciences;* i.e., on the basis of perfectly comparable subsystems the following considerations must be respected [1]:

- *The judgment of direct causality*: "given certain conditions X, certain events tend to result in certain consequences Y." This means that a dreaded event (e.g., climate change) can be explained by the identification of a discrete and datable set of events preceding its occurrence (causes) and may generate expected consequences categorized in a discrete and datable unit of events. Let us note that to establish a "cause / consequence relation" answering the primary form "if X, then Y," it is necessary to respect the double validation of "necessary" and "sufficiency".
- *The judgment of pseudo causality*: while it is possible to identify a set of "agitator agents" with an impact on the explanation of the dreaded event, these provocative agents highlight, at most, a set of correlations.

The following factors make it difficult to apply and reduce the climate change problematic into a causal structure [1,7]:

- The possibility of finding different "causes," according to the different cultures and social behaviors considered to be standard. The consequences paths are hard to define and to imagine (limited knowledge) and could trigger unexpected phenomena with complex consequences.
- Human and/or social behavior entail interaction and feedback in quantities that exceed the framework of linear causality. The earth system is also under such causalities.
- Global climate and earth system are *open systems*.

Do these theoretical concerns mean that it is illusory to fight against climate change by taking local action?

We do not think so. For social reasons, the majority of the earth population lives in poverty, for environmental reasons with the need to reduce pollution and by the

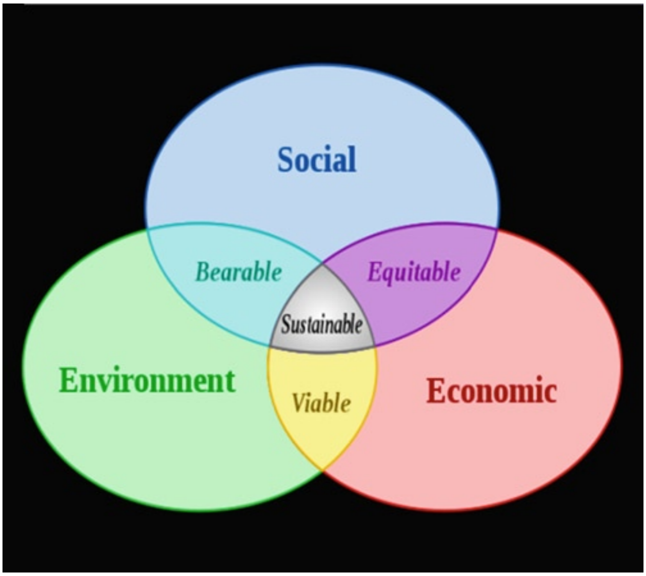

Fig. 11.1 SD principle

fact that resources on earth are limited and will impose changes. Indeed we are probably at the age of a collapse and as Jared Diamond [4] observes, the question might be "how societies choose to fail or succeed". We are therefore in the situation of having to prevent a catastrophe by supporting a "*catastrophisme éclairé*" [5] (facing catastrophe's possibilities). It is not a pessimistic bias and it fits too with the assumption of Edgar Morin [12] that it is sometimes on the edge of the cliff that the transformation will be possible.

However, it seems necessary to insist first on the fact that climate change is also the result of social and human behavior that cannot be reduced to the presupposed argument of determinism [2]. That means that we should find approaches to help stakeholders become aware of the global impact of their actions. Second, managing the risk of climate change requires the development of new methodologies.

11.2.2 How Sustainable Development Principles and Framework Can Support Decision Making Under Uncertainty

The implementation of the SD Principle invites an in-depth change in the way organizations are managed. Each decision taken must consider the potential impacts of environmental, social, and economic dimensions (Fig. 11.1).

It is not new in itself to make tradeoffs between different issues. However, the approaches and methods for ranking and weighting the stakes within a new paradigm (sustainable development) may be revolutionary.

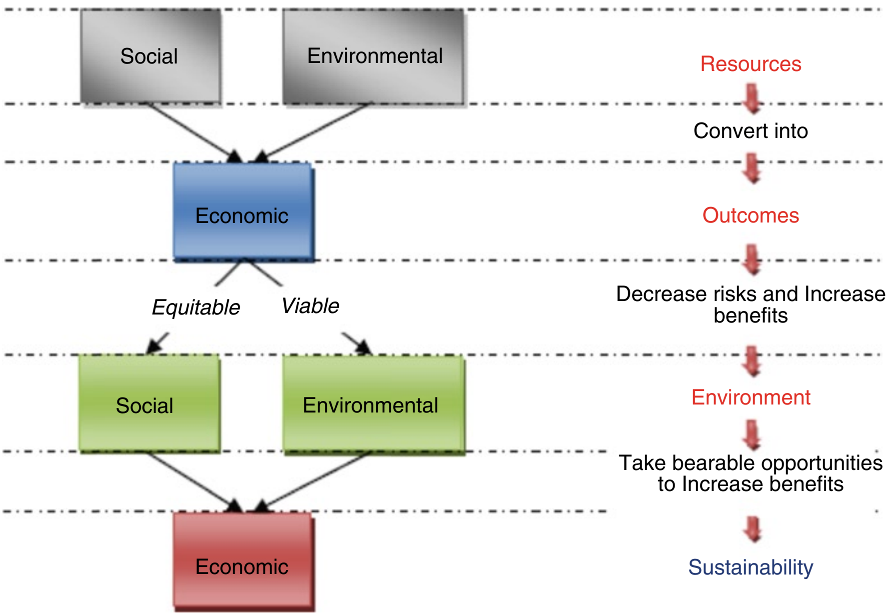

Fig. 11.2 The implementation of the SD principle within an organization

Sustainable development is an ethical principle before it is an action principle. In fact, being able to establish a balance between the three dimensions listed below needs a strong strategic engagement. In addition, management of organizations according to the SD Principle needs to transition from a classical economic view of organizations, where the environmental and social dimensions are considered infinite resources and economic benefits are the only measurable result, to a pragmatic view in which these resources are considered rare and vulnerable.

This point of view means that both opportunities and risks must be considered when exploiting environmental and social resources and the same reflections must be considered for the economic dimension (see Fig. 11.2). The following schema summarizes the implementation of the SD Principle within an organization (Fig. 11.2).

Implementing those changes in an organization will not be an automatic result of priority changes. Changes to some management and decision-making processes are required to increase the involvement of interested parties and stakeholders, especially in social and environmental arenas. Therefore, the approaches and governance frameworks promoted under sustainable development principles are required.

The managerial paradigm change motivated by the SD Principle increases uncertainty. Basically, the number and influence of new decision-making parameters have increased. Further, as implementing sustainable development is an innovative approach that requires invention of "a new way of doing things around here" or culture, there is a lack of experience, standards, criteria, and frames of reference, which brings new uncertainties [9] (epistemic and translational). To cope with those new uncertainties, a constructivist approach that relies on participative approaches and governance frameworks may be developed. New experiences will bring new perceptions of criteria and sustainable development plan implementation will be iterative.

Approaches that enable stakeholders to express preferences in decision making, understand organizational dynamics, and build participative frameworks are required. In the following section, we discuss the experience of framing a sustainable development plan within a public institution using a multiple-criteria decision aid methodology, participative approaches, and organizational analysis.

11.3 Example of the Implementation of the SD Principle in a Public Institution

11.3.1 Organizational Context

INERIS is a public institution in the field of industrial environment and risks, and provides technical support to the French ministry of Environment. As a public institute, INERIS must be exemplary when it comes to the implementation of the SD Principle. This implementation builds on a history of good practices:

- Since 2000, the Institute has been ISO 9001 certified and it regularly widens the field of its recognition relating to service quality, such as accreditation NF IN 45011 and ISO CEI 17025 for good laboratory practices.
- In 2001, the Institute signed a Deontology Charter formalizing the ethical values shared by all of its personnel and guiding its missions.
- In 2007, INERIS signed the Charter of Public Expertise with other public organizations, thus posting its commitment to share expertise with other stakeholders, such as NGOs.
- In 2008, the INERIS also signed, with other public organizations, the Sustainable Development Charter, which reinforces the Institute's commitment to the SD Principle.

In a letter addressed to INERIS in April 6, 2009, the French Ministry of Environment invited the Institute to frame a Sustainable Development Plan (SDP), including the following components:

- Identify strategic objectives.
- List a set of actions to meet three priorities (responsible sourcing, eco-responsibility, social responsibility).
- Identify a set of indicators to manage the execution of the actions at an operational level.

Although the SD Principle has been known and defined since 1987 by the Brundtland reports, it is quite innovative for a French public organization to make explicit and rationalize a set of actions to be carried out each year to contribute to sustainable development in economic, social, and environmental terms. Basically, several questions are raised such as: On what reference basis can we identify all the possible actions at INERIS? How can we rank the actions from the most beneficial actions to the less beneficial ones? What is the detailed set of criteria within a sustainable development policy? In what follows, we detail the use of some decision aiding methods to rationalize the sustainable development plan framing. Before this, we briefly describe our macroscopic approach.

11.3.2 Main Features of a Global Approach to Frame a Sustainable Development Plan

We have chosen to use a participative approach to develop a set of good practices and to identify the expectations of internal and external stakeholders. This approach includes a set of interviews and discussion groups.

Actions to implement the SD Principle within the INERIS organization are those that contribute to improve the equilibrium between environmental, social, and economic constraints. An organizational analysis carried out within the Institute helped us to identify initially almost 200 and later grouped into 48 staff-proposed actions [10].

11.3.3 Use of Electre III Mcap for the Ranking of Sustainable Development Actions for All the Institute

The staff-proposed list of 48 actions was then reduced by the top Director to a list of 22 key actions respecting the constraints made by the Ministry of Environment (Table 11.1).

These actions are the responsibility of the Institute's top management staff. Each division's director has a different role and perspective but shares common tasks that entail achieving the division's financial equilibrium and defining a strategic vision.

11.3.4 Set of Criteria and Weighting

These actions are coordinated by the General Director and his advisory board (Staff of Directors). Criteria were needed to organize a discussion by the Staff of Directors and compare one action to the other according to different points of view. Two main sets of criteria were applied:

- Expected benefits due to the implementation of sustainable development actions.
- Necessary expenses due to the implementation of sustainable development actions.

The 22 sustainable development actions were assessed according to three benefit criteria and three cost (expenses) criteria.

Table 11.1 List of 22 sustainable development actions for INERIS

		SD domains		
Id.	Description	Environmental	Social	Economic
1	Office automation: for 2010, 60% of new-bought materials must perform equivalent to the TCO Swedish reference, and include a minimum percentage of recycled materials	✓		
2	Increase the percentage of organic products offered by the Institute's food services	✓	✓	
3	Check the origins of wooden products	✓	✓	
4	Use eco-labeled products for building cleaning	✓		
5	Limit the use of paper	✓		
6	To train the staff in eco-driving (lower gas consumption) during work displacements	✓		
7	Limit vehicles (private cars) to those emitting less than 130 g of CO_2/km	✓		
8	Implement a company displacement plan (carpooling, company bus)	✓		
9	Control waste management	✓		
10	Reasonably manage the Institute's parks and tree inventory	✓		
11	Remove ink-jet printers in 2010	✓		
12	Limit energy consumption by Institute buildings	✓		
13	Implement a durable sourcing policy			✓
14	Contribute to the development solidarity and social economy (provide social services to employees)		✓	✓
15	Consolidate partnerships with the different sustainable development actors		✓	
16	Develop new managerial practices with respect to the SD principle		✓	
17	Develop better career management policies and improve employee well being		✓	
18	Invest the Institute in social responsibility by integrating disabled employees into the workforce		✓	
19	Strategically monitor the field of sustainable development to support Institute project leaders and managers		✓	✓
20	Develop knowledge exchanges with our foreign partners to capitalize on good practices		✓	
21	Reinforce the links between INERIS and NGOs		✓	
22	Develop a sustainable development culture within the Institute.		✓	

11.3.4.1 Set of Benefit Criteria

The 22 actions all have *positive impacts in terms of environmental, social, and economic responsibility* that can be estimated qualitatively. Each action is assigned a value between 1 (the impact is difficult to estimate or no impact) and 4 (high impact) (Fig. 11.3):

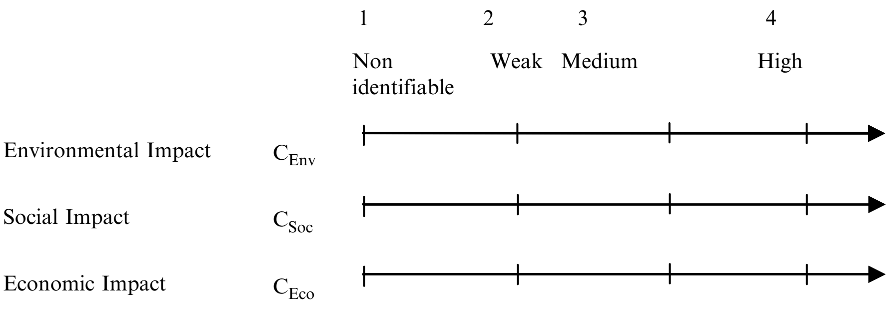

Fig. 11.3 Set of benefit criteria

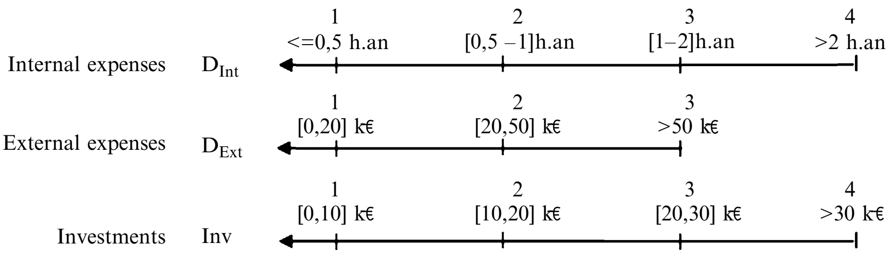

Fig. 11.4 Set of cost criteria

11.3.4.2 Set of Expense (Cost) Criteria

Implementation of the 22 actions will represent an expense for the Institute. As presented below, three categories were used to estimate the expenses required for the implementation of the sustainable development actions: Internal Expenses (work done by the Institute staff), External Expenses (e.g., scientific and technical subcontracting), and Investments (e.g., equipment).

Each action is assigned a value from 0 (not possible to assess) or 1 (low) to 4 (high) for Internal Expenses and Investment, and a value from 0 (not possible to assess) or 1 (low) to 3 (high) for External Expenses. External Expenses and Investments are estimated in K€. Internal Expenses are estimated in man/year (Fig. 11.4).

Use of criteria-specific weighting required use of a formal multi-criteria decision-making methodology with the Staff of Directors. The cards method [8,9,11] is well-adapted to ELECTRE III and can help to frame a common representation of the sustainable development strategic problem for stakeholders. Each criterion is associated with a card. The directors are asked to sort the cards from the least important to the most important and to insert blank cards to indicate the transition from one rank to the next. This revised Simos method [11] has many advantages, including preventing criteria from being eliminated by a zero-weight assignment and incorporating the various weightings assigned by directors as a function of their expectations and preferences [8]. This method was applied separately to obtain one weighting for the benefit criteria and another weighting for the cost criteria (Table 11.2). Each of the three benefit criteria has an equivalent weight with respect to determining the priority of sustainable development actions. The weight of each cost criterion was expected to be consistent with $D_{Int} = Inv > D_{Ext.}$. That is, the Staff of Directors prefers to plan for internal financial investments or leverage internal staff (technicians or engineers) time rather than pay for external consulting to implement an action.

11.3.5 From a Partial to a Global Assessment of the Sustainable Development Actions

At this level of decision making (strategic and tactical), most of the available information is qualitative. This is mostly due to the need to frame a common representation of strategic objective of the Institute once the actions are identified and the criteria specified. The Institute is familiar with ELECTRE methods, so we decided to use ELECTRE III [9].

By conducting a set of interviews with the staff of Directors, it was possible to fill out the sustainable development actions dashboard. Each action is coordinated by a Director**.** Each Director estimated the sustainable development action according to the two sets of criteria. These assessments are carried out once per year and synthesized in "Impacts SD dashboard" (Table 11.2).

Each action is compared to the other according to the set of criteria defined in the table below. After discussion with the Staff of Directors we have been able to fix equivalence and preference thresholds for each qualitative criterion.

The ELECTRE III method was run twice using the software ELECTRE III/V Version 3.1b for each set of criteria. Two credibility indices, $\sigma(a_i,a_j)$ and $\sigma(a_j,a_i)$,[1] are calculated each time for each pair of actions (a_i and a_j) of the 22 actions presented in Table 11.2. This calculation allows definition of an outranking relation among all the actions. It then became possible to draw up both a partial pre-order (making it possible to compare two actions and a final pre-order) presented in Table 11.3.

This table triggered a debate among the Staff of Directors. Actions 5, 7, 8, 11, 12 and 21 were considered—before explaining their preferences—the most important actions required to become an OSR. The great majority of these actions are eco-responsible, meaning that they are considered to principally affect the environmental sphere, and therefore reduce the risk of climate change. In fact, interviews with internal and external actors show that the minimum set of actions required to apply the SD Principle are different, and listed below. The application of Action 5, "Control

[1] The credibility indices allow estimation of the degree to which it is possible to say that an action a*i* is considered more important than the action a*j* according to the fixed set of criteria.

Table 11.2 Impacts SD dashboard

ID. SD Actions	C_{ENV}	C_{SOC}	C_{ECO}	D_{INT}	D_{EXT}	INV
1	4	1	1	0	0	1
2	4	3	1	0	3	1
3	3	3	1	0	2	2
4	3	1	1	0	1	0
5	4	1	1	1	2	0
6	1	2	1	1	1	0
7	3	1	1	0	0	2
8	2	4	3	1	0	2
9	3	2	1	1	2	4
10	4	1	2	1	0	0
11	3	1	1	1	1	0
12	4	2	3	0	0	4
13	1	3	2	1	0	1
14	1	4	3	0	1	0
15	1	3	3	2	0	0
16	2	4	2	1	1	0
17	1	4	3	1	1	0
18	1	4	1	1	0	1
19	1	3	3	1	0	1
20	1	3	1	1	0	0
21	1	3	2	2	0	0
22	3	4	4	1	1	0
Thresholds						
Q	1	1	1	1	1	1
P	1	1	1	1	1	1
Weights	100	100	100	62	38	62

Table 11.3 Ranking of the actions according to two sets of criteria

Final pre-order (rank)	Priority order on actions according to benefit criteria	Priority order on actions according to cost criteria
1	22	14 and 4
2	**12** and 8	10, 20 and 1
3	14, 2 and 17	11, 6, 16, 17 and 22
4	3 and 16	13, 18 and 19
5	9, 15 and 19	15, 21 and 7
6	10	5 and 8
7	1 and 5	**12** and 2
8	13, 11, 4, 7 and 21	3
9	18	9
10	20	
11	6	

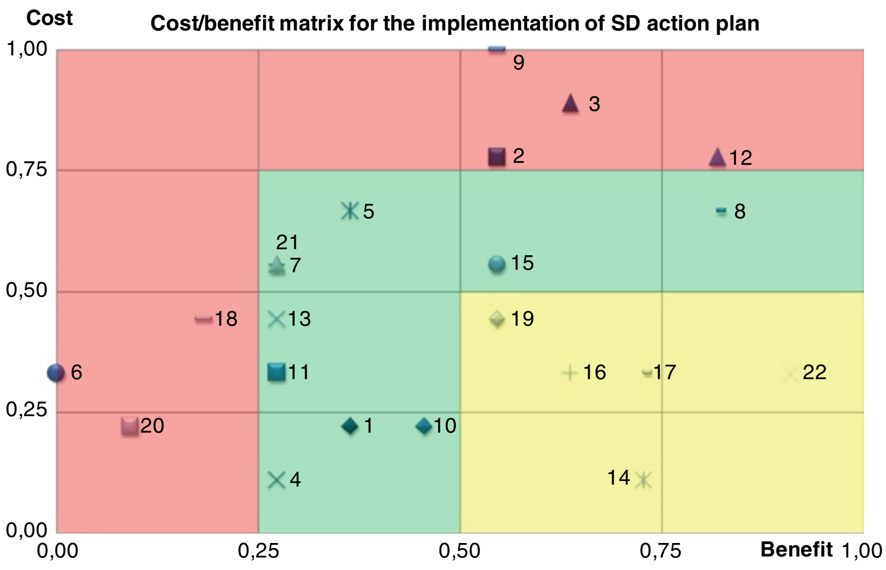

Fig. 11.5 Matrix to choose the best cost/benefit relation for the 22 SD actions

the use of paper," is now considered as one of the key performance indicator of the Institute and is even introduced in the calculation of the profit-sharing of the workers of the Institute. Action 8, "Implement a Company Displacement and Transportation Plan," is seen as one of the most beneficial actions (rank 2), but needs investments. This action has been given overwhelming support by the French government, which considers it an interesting strategy to reduce CO_2 emission due to commuting.

Action 14, which entails development of a solidarity and social economy (e.g., provide social services to the Institute workers like a caretaker's lodge or give support to families with a handicapped child) was at first considered insignificant. Its ranking shows that this action does not require a lot of investment but can have important impacts on working conditions within the Institute.

Action 12, "Limit the energy consumption of Institute buildings," was considered a leading 2008–2009 action for the implementation of the eco-responsibility principle. The Institute's Facility Manager is in charge of the implementation of this action.

11.3.6 Discussion of the Results

Surprisingly, actions 14, 16, 17, 19, and 22, which offer the most interesting ratio between benefits and costs (see Fig. 11.5), were neglected by the staff of Directors.

These actions are most beneficial at a social level (see Table 11.1) and act on the *sustainable development culture* dimension, but have indirect impacts on reducing the risk of climate change.

One can assume that the actions assigned higher priority are influenced, as discussed in Sect. 11.1, by media perceptions and the social construction of sustainable development, with significant weight given to environmental criteria and measures. Thus, the actions considered most important are those with the most direct impact on climate change: improving energy efficiency and lowering carbon dioxide generation. Those lasting measures tend to be considered the most useful within many organizations as they also have a strong impact on economic dimensions by reducing expenses and saving money.

The preference for these techno-centered measures over organizational and/or behavioral and cultural ones is consistent with the tendency of the industrial sector to prefer technical measures when dealing with safety; this is true even though learning from accidents indicates that human, organizational, and societal dimensions are central but corrective actions remain mainly technical [3].

11.4 Conclusions

This paper discussed some conclusions of a research-intervention project implemented in 2009 to define a sustainable development strategy and among other issues addresses the fight against climate change by a public organization under the "Grenelle 1" Act.

The sustainable development principle remains difficult to implement within organizations as it is very new and brings a lot of uncertainty without much experience or standards. There is rarely an optimal solution for sustainable development. Most frequently, there is a need to build compromises between conflicting concerns, such as economic, social, and environmental ones.

In this paper we have also discussed the complexity of sustainable development problematics and the necessity to develop adaptive methods and tools helping organizations to reach an equilibrium among the environmental, economic, and social risks posed by climate change. This requires involving new stakeholders and developing participative approaches and governance. To support this process, an organizational analysis was completed.

The detailed example of a public institute was presented and a Multi-Criteria Decision Aid (MCDA) methodology based on an ELECTRE III aggregation procedure was implemented to rank sustainable development actions and deal with this complexity.

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Chapter 12
Adapting Cities to Climate Change

Understanding Resilience at the Local Level

L. Yumagulova

Abstract As our urban systems get more complex and interdependent, they become more vulnerable to both external and internal disturbances. These disturbances have the potential to qualitatively change the system; but, if the system is resilient, it can absorb the disturbance and continue its operation.

Due to climate change, cities are currently facing unprecedented environmental change and previous models designed around a linear understanding of change as incremental and predictable might not be flexible enough to respond to this change. Therefore, a new, fundamentally nonlinear, way of dealing with change in cities is required. While a great uncertainty prevails regarding the impacts of climate change particularly at the local level, it is agreed that climate change amplifies already existing threats and magnifies the needs of the most poor. However, climate change can also serve as an opportunity. The extent to which institutions and citizens take an advantage of this opportunity depends on two fundamental pillars of adaptation: the ability to understand and the ability to respond to change, both of which are addressed in the detail in this chapter.

12.1 Introduction

Cities play an important role in addressing the climate change challenge. As engines of economic growth they are responsible for a large proportion of greenhouse gas emissions. At the same time, as home to over 50% of the global population, cities

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face serious challenges in reducing the vulnerability of urban residents to the direct and indirect impacts of climate change. Mitigation and adaptation are considered to be the two fundamental policy approaches for reducing the environmental, economic and social threats posed by climate change [38, 63]. Some have argued that to date, much of the emphasis in planning for climate change in cities has been focused on reducing greenhouse gas emissions—mitigation [49, 90]. Adaptation has received much less attention by political decision makers and planners at the city level [32, 49, 62, 84, 85]. At the same time, there is a recognition that urban areas are at particular risk from changing climate [43, 66, 79] with the greatest threat to urban areas arising in countries and regions that already suffer from regularly occurring natural disasters and the urban poor being most at risk [90]. While the scientific consensus of the impacts of climate change at the global scale is uncertain, things are even more complicated at the local-regional scale, where there is a lack of understanding of the direction of change, let alone its magnitude [40]. Yet, this is the level where planning and land-use decisions are made [40]; decisions that affect both mitigation and adaptation options. Roberts [86], drawing on experience in Durban, South Africa, stresses that without developing a meaningful understanding of the science, climate change and its significance are unlikely to be effectively understood and acted upon at the local government level. The climatic uncertainties at the local level are compounded by uncertainties in the political sphere, institutional and technological change, and evolving societal values and economic fluctuations at the local as well as global scales [40]. Considering these pressing challenges and the limited resources that cities have, the long-term nature of planning for climate change often does not get enough attention or political will during short-lived office-terms. Building supportive institutions that are capable of dealing with changing environmental risk and preparing to adopt new basic operating assumptions are the key challenges of adaptability [6, 18, 40, 50].

This chapter highlights some of the main adaptation challenges that cities face in a changing climate. In this chapter, adaptation is understood as change in response to environmental conditions, which maintains, preserves, and enhances the viability of the system of interest [97]. Adaptation can be analyzed in three major dimensions: the characteristics of the impacted system, the attributes of perturbation, and the nature of the response [97]. This chapter addresses these three dimensions in an urban context in corresponding themes: (1) climate change as a needs magnifier that highlights population groups that are particularly vulnerable in a changing climate; (2) climate change as a threats amplifier that discusses the implications of changing environmental risk in cities; (3) climate change as an opportunity. As the discussion below will show, the first two themes dominate urban climate change adaptation research. The third section draws on a smaller but growing set of academic literature as well as practical examples of addressing climate change as an opportunity. These sections set the context for the main part of the chapter which deals with the concept of change—one of the fundamental concepts for understanding adaptation. First, the ways in which change has been conceptualized is analyzed, which is important as this determines the nature of the response to change. Then various frameworks developed for responding to change and uncertainty are critically evaluated against the background of current policies and institutions dealing with climatic variability. The emphasis in this chapter is placed on *resilience* as the strategy in responding to climate change challenges at the local level.

12.2 Climate Change as a Threats Amplifier

The United Nations estimates that currently around 70% of disasters are climate-related compared to 50% in the 1980s [101].

Most of the risks from climate change amplify other risks already present [90]. As the Global Leadership for Climate Action report [33] suggests:

> …climate change is primarily a multiplier of known risks that have in the past rarely received sufficient attention or funding because they have fallen in the gap between disaster relief and development.

While every city will experience effects from climate change, some areas will be the most vulnerable. The scope and scale of the impacts may vary depending on a variety of factors ranging from geographic location to societal organization. From the geographic point of view, cities located on coasts and river flood plains and other areas prone to extreme weather events, especially where rapid urbanization is occurring, are most obviously at risk [51]. However, cities whose economies are based on the availability of climate-sensitive resources or those located in areas of decreasing precipitation are also vulnerable [106].[1] Some of the main challenges and differences that climate change poses to coastal and inland systems are discussed in detail elsewhere in this volume. Overall, cities, depending on the their geographic location, can expect to experience the following effects [20, 51]:

- Increase of hot extremes, heat waves and droughts, intensified heat-island effects
- A rise in sea level during the twenty-first century of approximately 0.2–0.6 m
- Increased severity of hydrometeorological hazards
- Increased disruption to critical infrastructure systems by extreme weather
- Increased likelihood of building subsidence on clay soils
- Continuing qualitative changes in ecosystems, leading to an increase of surprises

Considering the uncertainties involved in these effects, a large proportion of climate change science is devoted to modeling and prediction. This can be

[1] It is important to note that the challenge of the changing climate is not only about the extreme changes in weather. Even unspectacular climatic anomalies such as changes in the means, which the general public perceives as unusual rather than catastrophic weather conditions (3°C increase during the months of July and August), can cause disastrous losses. The losses and damages of the warm summer of 1995 in the UK exceeded GBP 1.5 billion for England and Wales [60].

explained as a need for solid scientific evidence as a basis for policies and action. At the same time:

> …models cannot be expected to identify the full range of potentially knowable climate surprises, let alone their first- and second-order effects on ecosystems and societies [100].

A standard argument of those seeking to play down concern about hazards—as well as by those wanting to increase this concern—is to draw attention to the inevitable scientific uncertainty [40]. At the local level the uncertainty argument is being increasingly understood as an excuse for inaction as the First Annual Mayors Adaptation Forum held in May, 2010, in Bonn, Germany, has shown. Mayors from around the globe took the historic step of signing the Bonn Declaration of Mayor Adaptation Forum 2010 with the intent of proactively addressing the climate change challenge at the city level. The Declaration recognizes that "climate change is real, global and immediate. Our cities are at risk. Local level adaptation is essential."

The Declaration pays significant attention to financing local adaptation plans for mobilizing local resources to gain direct access to financing mechanisms from multilateral and national levels. It calls for the integration of local adaptation strategies with sustainability principles and addressing the needs of the urban poor, who are most vulnerable to the impacts of climate change.

12.3 Climate Change as a Needs Magnifier

According to United Nations projections, every week over the next 30 years, the global urban population will grow by one million [111]. The historic rates of urbanization and current projections have massive implications for the socioecological dynamics of the planet: from a 3% urban population in 1800 to 14% in 1900 to 50% in 2008 and to a UN projected dynamic equilibrium of 80% urban to 20% rural [34]. This rate of urbanization will result in an increased number of natural disasters in cities, as a result of the concentration of people and assets in hazardous areas [66, 79, 111]: lack of space for further expansion of the cities will force development in floodplain areas and lowlands previously in nonurban use. As land pressures in the city grow, informal settlements (or slums) will be forced into even more formerly uninhabitable areas of high disaster risk: swamps, floodplains, steep hillsides, or municipal dumps [34]. The majority of the world's fastest growing cities—88%—are exposed to natural disasters and all of them are located in developing countries [23]. These urbanization challenges are coupled with the uncertainties of the changing climate. However, despite major uncertainties in the predictions of long-term climate developments and their consequences at regional and local levels, the need to adapt to climate change is becoming increasingly clear. Recent scientific evidence of the growing intensity of natural hazards due to climate change [26, 105] and recent events such as the 2010 Pakistan floods and 2010 fires in Russia suggests that the severity of natural hazards will continue to overwhelm the human capacity to deal with extreme changes in the environment. The connection between climate change, the risk of natural disasters, and resilience in the cities is the central theme of this chapter.

12.3.1 The Urban Context of Vulnerability and Disasters

The main impacts of climate change are likely to be increased levels of risk from existing hazards. The distribution of these risks will affect the poor the most. Some of the impacts are very direct—more frequent and hazardous floods—but some are more indirect, such as reduced availability of freshwater supplies for cities, an impact that will increase costs to the poor [90]. Adaptation to a wide variety of risks, or, as Sanderson [89] suggests, "managing disasters," is an everyday occurrence for millions of poor urban dwellers. Hewitt [44] finds these disasters created by everyday life, in chronic areas of neglect and in disregarded implications of social change. The urban context of vulnerability can be characterized by the concentration of multiple hazards [17] that have complex interconnections, making it difficult to identify risk and reduce vulnerability. Pelling [79] decomposes vulnerability into three constituents: exposure (a product of physical location and environmental surroundings), resistance (a capacity to withstand the impact of hazard based on the livelihood portfolio), and resilience (the ability to cope or adapt to environmental risk). These three constituents are shaped by access to rights, resources, and assets. According to Moser [67], the asset portfolio of urban populations include labour, human capital, housing, household relations, and social capital.

The "coevolution of urbanization and risk" [79] affects the creation of vulnerability and serves as an "interactive context for disaster" [66]. Moser [67] identifies three distinguishing aspects of urban vulnerability: (1) almost total dependence on money in city economies; (2) complexity of environmental risk; and (3) social fragmentation, especially among low-income urban settlements that are often characterized as having limited social assets. The urban poor also have problematic relationships with local government—an institution that is supposed to act to reduce climatic risks at the local level [90]. The relationship with the government is very place-specific from best, for example, in Turkey, which offers a standard method for new squatter cities to form; to worst, for example, in Kenya, which actively prevents squatters from improving their homes [34]. Living in informal settlements (on the sites most at risk from climatic change) and working in an informal economy makes the urban poor particularly vulnerable to changes in their environment—physical, social, political, and economic [90]. However, it is important to acknowledge that despite the lack of the formal plans and infrastructure, informal settlement are not exclusively places of poverty and risk—these settlements are also dynamic places of social innovation and creativity [62]. As such they are:

> …a reminder that different social forms might yield identical functions; that the ability of social institutions to change in form yet continue to yield comparable institutional functions is a key element to the adaptive capacity of urban social–ecological systems [34].

While these issues are a familiar refrain in developing countries, Hurricane Katrina has shown their prominence in developed countries as well, where the vulnerability of low-income groups combined with a lack of investment in the flood defences, degradation of the coastal environment and an inadequate capacity of the emergency services at various levels created a favourable context for disaster.

Climate change exacerbates the needs of those most in need as outlined in this section. It also further deepens the complexity of the environmental risks that are imposed on these vulnerable groups. However, a small set of literature and certain exemplary cities (for example, Sorsogon City, the Philippines) suggest that climate change presents an opportunity to address these growing needs through urban planning.

12.4 Climate Change as an Opportunity

The challenges that cities face due to their high concentration of people, complex governance systems, and dependence on infrastructure systems will require a specific set of adaptation strategies that can insure flexibility in addressing the changing nature of environmental risk. For example, the current practice of designing critical infrastructure based on past climatic conditions that are no longer accurate indicators for planning, maintenance, and upgrading has to be reconsidered [86]. Climate change will exacerbate existing urban challenges and environmental stressors. However, it also provides an opportunity for cities, as centers of innovation and human capital, by highlighting the need to address long-term development challenges, encouraging infrastructure investments, and improving urban planning and regulation [87].

The concept of adaptation to environmental risk needs to consider not only the ability to respond to perturbations but to take advantage of any opportunities that arise from these disturbances: adaptation includes processes that allow societies to survive, flourish, and maintain the quality of life [71]. Disturbances can provide the opportunity for creativity, innovation, and development, such as the emergence of a given social group from chronic poverty or the collapse of an oppressive regime [31]. In recent decades the concept of resilience is gaining currency as a frame for understanding adaptive changes in socioecological systems [2, 3, 8, 9, 10, 36, 39, 46, 48, 54, 72]. Resilience refers to the capacity of a system to absorb disturbance and still retain its basic functions. As Nelson et al. [71] suggest:

> …managing for resilience requires directing a system in a way that provides flexibility during times of disturbance and that allows a way to take advantage of the latent diversity within the system and the range of opportunities following release.

Typical examples of increasing resilience to climate change impacts at the city level include increasing the robustness of infrastructure, enhancing the protective functions of ecosystems, incorporating climatic risks in urban planning and management, market solutions, establishing emergency funds, improving societal awareness and preparedness, reducing institutional fragmentation, and creating policy frameworks for disaster management [58]. UN-Habitat [104] provides the following examples on the ground of increasing resilience to the impacts of climate change: planning and land use controls to prevent people from building in high-risk zones (e.g., restrictions on building within 50-year floodplains in South Africa); change in building codes and regulations; for example, 2006 Thua Thien Hue provincial regulations in Vietnam encouraging cyclone-resistant building practices. Some promising examples of built-in adaptability also exist in Europe:

> … while most American cities are just at the point of taking stock of the magnitude of their exposure to climate change… European cities have acted and offer practical lessons learned [45].

For example, HafenCity is located in the old harbor of Hamburg, along the river Elbe in Germany. Known as one of the largest rebuilding projects in Europe in the twenty-first century, it has transformed the formerly inner-city port fringes into an adaptive urban environment. Its urban design will allow flooding, and will stay resilient to high water, with waterproof parking garages, a network of emergency pedestrian walkways 20 ft above the street, and no residential units at ground level [45]. The landscaping in the parks is specifically designed to withstand storm surge, either by floating as the waters rise, or by incorporating lots of hard surfaces that only need to be washed off when the waters recede [45].

> The intensive reciprocal interaction between land and water can be regarded as unique, for HafenCity will not be surrounded by dikes, nor cut off from the water. With the exception of the quays and promenades, the total area, i.e. streets, parks and development sites will be raised to 7.5 to 8 m above sea level. This creates a new, characteristic topography, also maintaining access to the water and emphasizing its typical port atmosphere [37].

One of the fundamentals of the project is "to see urban development as a learning process," ensuring an ability to recognize changes in the environment and to be able to respond.

Another example is climate-proofing in the Netherlands. If anybody knows how to adapt and to battle the changing risk, that would be the Dutch, as they firmly believe in their ability to live with the changing dynamics of water. As a Dutch saying goes, "God created the world, but the Dutch created the Netherlands," with all its vulnerabilities, opportunities and risks. "Rotterdam Climate Proof will make Rotterdam fully climate proof by 2025," begins a description of Rotterdam's climate-proof adaptation program [88]. Europe's biggest cargo port city, which houses an increasingly large portion of the Dutch population, is planning to protect the city from direct impacts of climate change (flooding, increased precipitation, groundwater salinization, heat waves) through innovative applications in the area of water management while making it more attractive. From water plazas to floating buildings and communities, Rotterdam is positioning itself as an example to follow as an international water knowledge and climate city. The main themes of the adaptation plan include: flood management, accessibility, adaptive building, the urban water system, and the urban climate. A major emphasis of the campaign is on marketing the strategy as an export product—for profit. As these examples show, climate change can be an opportunity for changing the status quo, for creating new learning opportunities, and for profit.

The extent to which climate change adaptation will be effective depends on an ability to understand projected climatic changes at geographic and temporal scales appropriate to the needed response [70]. The complex interactions between changes in climate and non-climate factors, such as demographics, economics, land use, and technology, ensure the intrinsic diversity in the impacts of climate change. Thus, effective approaches to adaptation will be case and place-specific [70]. This means that understanding the strategies for effective adaptation at the local level is one of the most important challenges that climate change poses.

Fundamentally, adaptation is about being able to understand the changes and plan responses to them. However, when uncertainty is high, rigid response strategies might only exacerbate vulnerability. A potentially more useful approach is designing flexible institutions that are able to respond to changed conditions and surprises and maintain the functionality of the system of interest. The ability to understand change and respond to it will determine whether climate change is an opportunity or a threat. In order for human systems to meaningfully engage with changes in environmental conditions, it is important to understand how *change* is being conceptualized and framed, as this determines response strategies. The remainder of the chapter deals with these two fundamental dimensions of climate change adaptation: understanding change and responding to it.

12.5 Understanding Change

One of the fundamental challenges that climate change poses is testing the limitation of human ability to deal with change. As noted above, adaptation is about being able to understand changing conditions and be able to respond to them. Adaptation is inherent to human nature as individuals, communities, and societies adjust their established practices to take advantage of new opportunities. However, adaption can be imposed on societies and localities because of external change leading to undesired impacts [71]. Some may argue that humans have been successfully adapting to hazards of changing climate for centuries. Virtually all of the great ancient civilizations (e.g., Chinese, Mayan, Egyptian, and Mesopotamian) directly intervened to mitigate the effects of natural disasters and governments have played a major role in developing elaborate systems of flood control [22]. Our urban centers have had to adapt to environmental conditions, site characteristics, natural-resource availabilities, and environmental hazards by, for example, creating stable sites for building, putting in infrastructure for provision of water, and processing wastewater as well as storm and surface runoff [90]. The first river dams and levees were constructed in the Middle East over 4,000 years ago and attempts to create earthquake-resistant buildings date back at least 2,000 years [96]. According to McDaniels and Small [61], "risk management has been a fundamental motivation for the development of social and governance structures over the last 10,000 years". More importantly, *understanding* of the threats has led to adaptive responses that open paths for change and innovation. Climate change, however, increases the complexity in identifying the range of impacts, the nature of the interactions with socioecological systems and the magnitude of consequences of the impacts (in terms of scale, location, timing, and frequency) [11]. While change is both dynamic and a constant of human societies [11], there is a growing consensus that the rate of change that society is increasingly facing is unprecedented [7, 19]. During the last 50 years, human activities have modified ecosystems around the world more rapidly and more extensively than at any other time in human history [19, 64, 99]. This has resulted in unpredictable qualitative changes in the behavior of ecosystems. This, coupled with the complexity of social systems, results in increasing uncertainty and a potential for qualitatively new, previously unexperienced events: surprise. As the International Geosphere-Biosphere Programme (IGBP) synthesis report suggests , the Earth System now has entered a "no-analogue state" [99], in which past behavior of the system can no longer serve as a reliable predictor of future behavior, even when circumstances are similar [28]. Furthermore, as noted elsewhere in this volume, a recent National Research Council [69] report explicitly states that our current decision making processes and institutions are not adequate to deal with changing climate. What can be done then if indeed "the conventional set of policy instruments, laws and institutional configurations used to address social problems" is impotent in the face of "processes of rapid, fundamental, and possibly detrimental change" [28]? This chapter deals with two dimensions that might contribute to answering this question: understanding change and responding to change.

12.5.1 Typology of Change

Since the 1980s, the concept of risk has been central to the explanation of changes and challenges in modern societies particularly in the relation between society and its natural environment [5]. Researchers recently pointed to the limits of the notion of risk as it has been used since the 1980s [13]. As mentioned above, there is a growing recognition that current institutions and policies designed around a linear understanding of change and risk are not adequate for dealing with current rates of change. A potentially more useful approach would be to design our policies around explicit recognition of the unknown and build in flexibility and mechanisms for learning and adaptation in these policies. In order to do this, a systematic recognition of the unknown and potential changes it might bring needs to be explored. One potential way of differentiating the unknown is as follows: (1) uncertainty, where the range of possible outcomes is known but probabilities cannot be assigned; (2) ambiguity, where incommensurable priorities or notions of harm prevail; and (3) ignorance, where neither outcome nor likelihoods are known (could also potentially include taboos (socially enforced ignorance) and distortion (deliberate attempts to maintain ignorance)) [98]; and (4) fundamentally new, never before experienced events—surprise [94]. As Handmer and Dovers [40] suggest, current policymaking processes are not good in recognizing and dealing with ignorance: it is ignored or denied or attempted to be reduced through scientific inquiry. The evolving, long-term nature of climate change, with its variable spatial and temporal effects and evolving responses, requires a dynamic framework for understanding change. Understanding change and the difference between static and evolutionary

Table 12.1 Typology of change/unknown [26, 35, 36, 47]

Linear understanding of change—risk	Events, processes or outcomes are known and probabilities are estimated from observed (stationary) data;
Uncertainty	Events, processes or outcomes are known but their probabilities are not known, or are assigned by subjective estimates.
Surprise	A condition in which perceived reality departs qualitatively from expectations; events, processes or outcomes are not known, and are unexpected.
Unexpected discrete events -Local surprise	These can often be addressed by recognizing broader scale processes and fluctuations of which there is little or no local knowledge.
Cross-scale surprise	Discontinuities in long term trends, abrupt and non-linear changes in behaviour of the system that, in hindsight, can be attributed to an interaction between key variables that operate at distinctly different scale ranges, where a faster variable interacts with a slower variable (analysis of qualitative shifts in stability domains of resource systems).
True novelty	Events outside the breadth of captured experience for a culture in a new situation (introduction of new technologies and subsequent social changes).
Crisis	Surprise becomes a crisis when it reveals an unambiguous failure of policy.

risk requires consideration of the continuum of knowledge between a linear understanding of change (known risks), uncertainty, and surprise [26, 35, 36, 47, 93].

Table 12.1 provides an initial framework for typology of the unknown and the changes it might bring.

According to Downing et al. [26], present extreme events should be considered in the first category. However, these authors suggest that considering the availability of only short time series of data and the evolving nature of natural and social systems, many of the distributions are uncertain. Projections of climate change, for mean conditions, are also uncertain, with an increased acknowledgement of surprise elements; for example, in large-scale changes in ocean circulation or economic sensitivity to climate impacts [26].

Thus, while it is agreed that climate change is indeed a threats amplifier, the interaction between the unknown magnitude of consequences of the impacts and the changing and evolving nature of the impacted systems increasingly provide more room for surprise. Acknowledging these surprise elements is fundamental to our adaptive capacity:

> …to draw some types of climate surprise into the realm of the predictable is to be able to conduct effective response planning and disaster mitigation [100].

Several taxonomies of surprise have been developed [15, 47, 52, 91, 92, 100, 102], which differentiate the degree of surprise and its origins. This chapter draws on this literature with a particular emphasis on the ecological studies of surprise presented in Table 12.1 and based on Gunderson [35]. Local surprises can be attributed to the lack of understanding of broader and longer-term processes and human limits on perception. An example of this type of surprise can be the local cycle of flood and drought in the southeastern USA due to El Nino/Southern Oscillation. Cross-scale surprise occurs when key variables, operating at different scale ranges, interact. The examples of this surprise include spatially contagious processes, such as forest fires or mountain pine beetle outbreaks. Finally, true novelty is a unique, previously unexperienced event that can generate change, the consequences of which are inherently unpredictable. This type of surprise is exemplified by new technologies, invasion of alien species, and the creation of new substances. The Eyjafjallajokull eruption and subsequent disruption of European airspace can also be attributed to this category. Of particular interest to this chapter is *climate surprise*, defined broadly as "a gap between one's expectations about the likely (i.e., plausible) climate and the climate that actually occurs" [100]; thus, *expectations* are key.

12.5.1.1 Anticipating Surprises

Clearly, surprises cannot be completely predictable. Schneider et al. [93] distinguish between *strict* and *imaginable* surprise. Strict surprise is wholly unexpected experience; therefore it has little policy relevance. The imaginable kind arises from imaginable conditions for surprise and has policy meaning as actions could be proposed to mitigate these conditions. Kates and Clark [52] suggest that there are a number of techniques that can be used to anticipate surprises, outlined below. *Surprise theory*, focuses on the principles underlying unexpected events and developments drawing on technological and ecological studies. *Historical retrodiction* examines empirical cases of surprise and attempts to determine whether the seeds of future surprises are apparent in hindsight and applies this knowledge to the future. The other methods that Kates and Clark [52] suggest are concerned with identifying trends and making projections based on them: introducing contrary assumptions, asking experts, using models of systems dynamics and, imaging, in which an unlikely event is postulated and attempts are made to construct a plausible scenario to explain it (a form of backcasting).

Among the most recent developments in anticipating surprises is a European Union- funded project: iknowfutures (http://wiwe.iknowfutures.eu/). This project:

> …aims to advance knowledge and tools related to events and developments (e.g., wild cards and weak signals potentially shaping and shaking the future of science, technology and innovation…

Wild cards are situations or events with perceived low probability of occurrence but potentially high impact if they were to occur. These range from threats (spread of the killer virus to devastation of Rome by an earthquake) to opportunities and innovation (from cars with eyes to the disappearance of male chauvinism). *Weak signals* are unclear observables warning us about the probability of future events (including wild cards). They implore us to consider alternate interpretations of an issue's evolution to gauge its potential impact. A sophisticated methodology, the science fiction flavor, and interactive design of this project create an interesting platform for anticipating surprises.

12.5.1.2 Surprise in the City

The nature and the scale of the surprise have significant implications for the functioning of the city, considering the limited financial resources and every day stresses and pressures that cities face. In analyzing capacities of cities to deal with surprise it is useful to think of cities as complex adaptive systems:

> …emergent, far from equilibrium, requiring enormous energies to maintain themselves, displaying patterns of inequality spawned through agglomeration and intense competition for space, and saturated flow systems that use capacity in what appear to be barely sustainable but paradoxically resilient networks [4].

Cities, as complex adaptive systems, could develop capacity to deal with uncertainties and surprise by increasing the system's resilience level.

According to Manojlovic [57], in resilient cities the urban fabric and people should be able to adjust to disturbance (short-term response), moderate potential damage, take advantage of opportunities [31], and to learn from that experience, and cope with changing conditions (long-term response). The systems approach conceptualizes cities as multilevel interacting systems composed of heterogenic elements that can be broadly classified as metabolic flows, governance networks, and social and built environment [57, 111]. These elements interact with each other at different temporal and spatial scales. The complex relationship between these elements is mediated through institutions: an increase or decrease of resilience in one of those main elements can affect the resilience of the whole system. Depending on the nature of the perturbation and characteristics of the system, the challenge is to define a set of measures and strategies that can increase the resilience level of urban systems while explicitly considering the nonlinearity of this relationship and increasing potential for surprise.

12.5.2 Crisis as a Window of Opportunity for Transformative Change and Innovation

The consequences of surprise are largely dependent on the nature of the response. Certain surprises can lead to a crisis, thus signifying an unambiguous failure of policy [47]. Some surprises may lead to a window of opportunity for changing shelved ideas and established practices. The examples of these vary in scale: from Greensburg, Kansas, US, where the city has chosen to rebuild green following a destructive hurricane, to a critical juncture; i.e., an irreversible change in the direction or composition of political regimes (Marmara earthquake, Turkey [82]). Kates and Clark [52] suggest that surprises are the primary source of increasing attention to environmental problems. They are key to changing our ideas and institutions (discovery of the ozone hole, Three Mile Island, Bhopal). This transformative potential of surprising events needs to be further explored.

In times of crisis, when uncertainty is high and control is weak, the future can be suddenly shaped by externally triggered events [48]. Therefore, conditions of crisis are not only negative. It can be a time for reorganization and innovation, and an opportunity for social and technological change, as previously established power blocs are weakened and fragmented, thus providing a space for new social arrangements to form [79]; a time for rejuvenation and the recovery of wisdom lost. It is therefore also a time when individual people have the greatest chance of influencing events [36]. Some crises can expose fundamental flaws in societal organization and therefore present unexpected opportunities to transform how systems operate and reinvent the entrenched paradigms.

Timmerman [102] differentiates surprises in their degree of impact: they can be considered *anomalies*; or produce *shocks*; generate *epiphanies*; or turn into *catastrophes*. Anomalies are "surprises that are marginal, puzzling, but not enough to alter perceptions." Shocks are surprises that "freeze the system or cause it to behave inappropriately". Epiphanies allow for deeper understanding of the "essential characteristics of the system dynamics in a useful way," thus allowing for constructive reshaping of expectations [100]. Catastrophes are "surprises that destroy a system before it can make any use of the event." Systematic learning from past epiphanies could help to avoid catastrophes and contribute to the resilience of socioecological systems. Thus, surprise can be positive, negative, or have mixed consequences [100]. The outcome is largely determined by the nature of the response to changed conditions. The remainder of this chapter analyzes key frameworks developed for responding to change and discusses some of the potential opportunities that climate change and associated surprises might bring.

12.6 Responding to Change

Response to change can range from short-term superficial adaptations to reduce vulnerability to the long-term, more fundamental changes that may be necessary for ensuring sustainability. Response can be reflexive (spontaneous, automatic, not thought through) or reflective (strategic and planned) [5]. The nature of change or perturbations that the systems of interest are going through can be broadly divided into stresses and shocks. Stress is a continuous or slowly increasing pressure, commonly within the range of normal variability, and often originates within the system [31]. Stresses may be gradual, not very visible, and therefore easy to ignore. An example of this in the climate change context would be increased temperatures, rising sea levels, soil erosion, and melting glaciers. Shocks, on the other hand, have heightened intensity, "beyond the normal range of variability in which the system operates and often originate beyond the systems or location in question" [31]. Shocks lead to increased impacts; for example, failure of critical infrastructure due to increased extreme weather conditions. When these shocks overwhelm expectations and capacity to respond, they turn into surprise.

Table 12.2 A typology of response to change

Type of change	Responding to change—adaptation strategies
Linear understanding of change—risk	Anticipation [107, 108]—detecting problems and trying to avoid them; Resistance [40].
Uncertainty	The precautionary principle [40], adaptive environmental management, the preventive paradigm or stewardship [16, 93].
Local surprise	…a range of adaptations to risk, that are amenable to economic rationality on an individual level, including risk-reducing strategies and risk spreading or risk pooling across independent individuals. [30] Manageable by individuals or associations of individuals.
Cross-scale surprise	Adaptation to this type of surprise requires coordinated collective action through existing or readily formed institutions [30], thus it is important to maintain institutional diversity as a reservoir of alternative strategies [73].
True novelty	Latent mechanisms for reorganization, learning, and renewal may provide a necessary capacity to deal with this type of surprise [30].
Crisis	A reinforcement of previous solutions, or the status quo; change at the margins or a window of opportunity for transformative change [40, 82, 83] .

Several conceptual frameworks have been developed for responding to change, which—less explicitly—deal with surprise. Table 12.2 presents a variety of response strategies for the risk-uncertainty-surprise continuum developed in the previous section (Table 12.1). These vary from anticipation of risk (in its static understanding), when it is believed that a very low level of ignorance is achievable [108], to potential responses to crisis that signals an unambiguous failure of policy as defined in Table 12.1. According to Schneider et al. [93], those in charge of environmental policy are often faced with the challenge of making decisions utilizing vague and ambiguous concepts (such as sustainability or resilience), based on sparse and imprecise information. These decisions often have far-reaching, irreversible impacts on both the environment and society. The precautionary principle [40], adaptive environmental management, the preventive paradigm, or stewardship [93] (Table 12.1) have become common policy strategies in attempts to reduce uncertainty and signal an acceptance of the inherent limitations of anticipatory knowledge in the field of global environmental change [110].

What follows is a detailed review of the potential responses to change presented in Table 12.2 with a specific emphasis on surprise as a category.

Wildawsky [107, 108] differentiates between two strategies of response to risk: anticipation and resilience. Anticipation seeks to preserve stability; implicit to this approach is the belief that a very low level of ignorance is achievable through identifying the unknown and then reducing or eliminating it through scientific inquiry. Resilience accommodates variability; a small number of regular disturbances can increase capacity to deal with future events, varying in their intensity. Wildavsky suggests that the experience of being able to overcome unexpected danger may increase long-term safety; but maintaining a state of continuous safety maybe extremely dangerous in the long run, since it reduces the capacity to cope with unexpected hazards. This understanding of human capacity to deal with uncertainties has significant policy implications: in an environment with periodic extremes where uncertainties are large, resilience is a preferred strategy. Under the conditions of low uncertainty about the future protection of the system against predictable forms of failure—anticipation makes more sense [108]. Kuhlicke [55], in his empirical study of the 2002 Mulde flood (Saxony, Germany), reveals that anticipation is an accepted and dominant adaptation strategy of citizens and decision makers. This is despite the fact that anticipation produces conditions of increasing vulnerability as it assumes citizens and decision makers have valid knowledge about the future. Considering recent scientific evidence of the "death of stationarity" [65] and the no-analogue state of the Earth-system [99], it seems as if the anticipation strategy might not be a wise investment. This has serious implications for the design of policies; for example, in water resource risk assessment and planning—as a significant amount of them are still based on stationarity as a central, default assumption [65]. According to Nelson et al. [71], much of the current research on adaptation implicitly focuses on minimizing exposure to specific risks through anticipatory action. The authors suggests that it is important to move away from strategies solely concerned with maintaining equilibrium and also begin preparation for surprises and system renewal.

A common response strategy aimed at reducing risks is diversification (as in an investment portfolio); it increases options for coping with change, shocks, stresses, and surprises by making systems less vulnerable [7]. By drawing comparisons between species in ecosystems and institutions in governance, Norberg et al. [73] provides two mutually related methods for sustaining diversity in socioecological systems:

1. Promoting local adaptations.
2. Enabling the diversity of local governance or decisions units in order to minimize the dominance of single solutions.

The authors argue that institutional diversity—"a reservoir of alternative strategies"—is an important source of more effective adaptations.

The diverse range of operational and collective choice rules that have been tried in a variety of contexts can enhance the system's adaptive capacity to respond to surprise, particularly of the cross-scale type (Table 12.2), "to alter the relative abundance of its components without significant changes in crucial system function" [73]. Diversity thus plays a central role in resilience. Much of the discussion so far points to a set of response strategies to the risk-uncertainty-surprise continuum within the frameworks offered by the notion of resilience. Considering the recent proliferation of literature and research on resilience, the following section provides a selective review of the key literature that is of particular relevance to this chapter and addresses:

1. Fundamental concepts derived from ecology—the origins—that are important for understanding resilience to natural hazards.
2. Global environmental change and institutional response to it.
3. The connection between resilience and climate change adaptation in cities.

12.6.1 Understanding Resilience

Building resilience into socioecological systems, as Tompkins and Adger [103] suggest, is an effective way to cope with unknowable risks and surprises. Resilience offers a different way of conceptualizing the complexity of the world through metaphors that assume change, not stability, is the norm in complex systems. Resilience—as both metaphor and policy goal—has developed from ecosystems theory but is increasingly employed to understand human systems. It can be measured by the amount of disturbance, or stress, that an (eco-)system can absorb without undergoing qualitative change [36]. Resilience in social systems has the added capacity of humans to anticipate and plan for the future.

There are three main factors that determine resilience of the system:

- The amount of change the system can undergo and still retain the same controls on function and structure.
- The degree to which the system is capable of self-organization.
- The ability to build and increase the capacity for learning and adaptation.

The four-phase adaptive cycle developed by Gunderson and Holling [36] is a key metaphor for understanding transformative change in complex adaptive systems. It suggests that change in most (eco-)systems occurs within a four-phase cycle of rapid growth, conservation, release, and reorganization. This lifecycle of the systems is determined by the three key ecosystem properties: potential available for other kinds of ecosystems and futures, degree of internal connectedness, and resilience. During the rapid growth phase, the components of the system are loosely interconnected and weakly regulated; resilience is high. During the conservation stage, energy and materials slowly accumulate, creating an increase in the potential for other kinds of ecosystems and futures.

As the system progresses through the conservation stage, the connectedness, stability and efficiency increase at the price of gradually loosing potential for quick adaptation. Increased stability/rigidity comes at a price of increased vulnerability to both internal and external disturbances. At a certain point, a critical threshold is reached; resilience of the system is overwhelmed by the disturbances, causing rapid change. Uncertainty is high but the accumulated energy and materials that are released create possibilities for reorganization. The system may collapse, or transform into a new system (similar or fundamentally different from the previous one). These adaptive cycles are *nested*, creating a *panarchy* [36] of interconnected and interdependent adaptive cycles across temporal and spatial scales. The phases of the adaptive cycle at various scales create opportunities for adaptation and reorganization of the entire system (for example, faster and smaller levels can transform larger and slower ones).

Resilience is a forward-looking concept that provides a way of thinking about policies for reducing vulnerability to future environmental change, "an important consideration in a world characterized by future surprises and unknowable risks" [7]. Adger [2] suggests that there is great heterogeneity in the structure of institutions that manage environmental risk and hazards, but little agreement among social scientists as to the processes by which institutional change reduces or amplifies risk. The next section explores the relationship between resilience and the capacity of institutions to respond to environmental risk and change.

12.6.1.1 Institutional Response to Environmental Change

The role of institutions in shaping vulnerability and influencing resilience has been discussed in a variety of contexts [1, 2, 12, 77, 79, 89]. Birkmann and Wisner [12] define institutions as "all public agencies dealing with risks on a collective level". Adger [2] accepts a broader definition and includes:

> …habitualized behaviour and rules and norms that govern society, as well as the more usual notion of formal institutions with memberships, constituencies and stakeholders [2].

Pelling et al. [83] differentiate between overtly formulated formal institutions that are "visible and subject to rational control and management through public institutional frameworks" and informal institutions that "include intangibles such as norms, values and accepted ways of doing things". Tompkins and Adger [103] distinguish between institutions at the community, formal-organizational and national regulatory levels and formulate the means by which institutions adapt to and learn in terms of networks of dependence and exchange. For the purposes of this chapter institutions are understood as the rules, norms, and strategies that govern human interactions [74, 76] in cities.

Resilience of the urban fabric is determined by institutional structures and urban governance [56, 79].The response of city governments to the needs of citizens is constrained with institutional, organizational, and financial limitations and depends on the legal and institutional framework, and the nature of political processes at the national and regional level, as well as local leadership [24, 79]. Understanding the pathways of response and resistance of the governance actors to change and mechanisms of institutional change is particularly important as it can enable meaningful engagement with change and promotion of transformative agendas [42].

A useful way of conceptualizing these pathways is provided by Handmer and Dovers [40] in their "typology of resilience". The first type of resilience, *resistance and maintenance*, is characterized by resistance to change: denying that the problem exists and spending resources on maintaining the status quo and enhancing the existing power structure. Examples of this type include the aid and insurance that flow into disaster-affected areas for building back to normal. The previous physical and social vulnerabilities are reconstructed; the position of those in power is enhanced; and the needs of those who suffered the most from disaster are unmet and deepened. Denial of external and internal changes and the inability to respond and adjust to new circumstances eventually can lead to a strained system that may collapse and change completely. Despite gloomly long-term projections, some of the positive features of this type of resilience include apparent short-term stability and certainty, enhanced optimizing capacity, and the impossibility of maladaptive change.

As an example, consider the collapse of the “hydraulic civilizations” [109] that failed to adapt to environmental change. These civilizations were characterized by massive investment in fixed infrastructure and social control. Power was maintained through exclusive control over water: flood protection and irrigation, were run by central coordination and specialized bureaucracy. These rigid systems collapsed, unable to respond to the changing environment, whether through the buildup of unaddressed gradual changes or unexpected episodic shocks [25]. Many of these examples exist for management of the environment and societies that lead to breakdown of socioecological systems: from suppressing natural disturbance regimes or altering slowly-changing ecological variables, leading to irreversible changes in soils, waters and biodiversity to governance systems that disrupt social memory and remove mechanisms for creative, adaptive response by people [29]. This type of resilience is least capable of dealing with surprise. According to Handmer and Dovers [40], this type of response to global environmental change is less prevalent today than the second type of resilience, which currently typifies the standard approach to risk.

The second type of resilience, *change at the margins,* is characterized by acknowledgement of the problem, discussion of its potential implications, and promulgation of the reforms that do not challenge the fundamental root causes of the problem but treat the symptoms instead. The emphasis is on the changes at the margins, which can be dangerous as it may create a false sense of security and fail to address the fundamental assumption in the operation of the system that has led to the problem in the first place. This is the most common type of response to environmental change, hazards, and risk. These responses are being shaped by what is perceived to be politically and economically feasible in the short term rather than by the nature and scale of the threat itself. While having obvious advantages, often described as “practical, realistic, balanced and pragmatic,” this approach only reduces vulnerability in the short term, putting off the need for a major change, which is likely to become increasingly urgent [40].

This type of resilience is dominant among current strategies for increasing resilience to climate change. Consider the following examples for increasing resilience [104]: to encourage climate-proof infrastructure: the US$ one billion Confederation Bridge in Canada, which was built 1 m higher than current conditions would require, accommodating anticipated sea-level rise. A cautionary note about over-reliance on technology has to be made as it can disregard uncertainty, leading to lock-in, create a false sense of security, and limit opportunities for adaptation in the future as suggested elsewhere in this volume. As Handmer and Dovers [40] suggest, instead of placing the emphasis on reducing uncertainty by tackling the physical source, the focus should be placed on institutional arrangements that allow adaptability by explicitly engaging with change. Consider London’s famous storm barrier on the Thames, built to protect billions of pounds worth of buildings and capital infrastructure and some 1.25 million people in the at-risk area. The barrier was designed to be able to cope with a one-in-a-thousand-year storm surge by 2030, yet fears exist that the sea is rising faster than was originally predicted in the 1970s, when the barrier was designed. The rates have almost doubled from1.8 mm a year then to 3.1 mm [21].

Currently, significant investments are being made to increase the protective mechanisms of the barriers. Therefore, building in flexibility has to become an important design factor for critical infrastructure.

For built-in flexibility, consider the Dujiangyan irrigation system in China (built in 251 BC) as an example of a sustainable drought control system resilient to large-scale flood. It was built in close consideration of the specific topography and natural environment, such as river depth and channel camber and out of simple local material (pebbles, stones, and bamboo) that allowed water and fish to flow freely underneath. The structure has been maintained without external expertise by local farmers for centuries. The flexible design also withstood the 2008 Sichuan Earthquake, which killed 40,000 people in the area. This example demonstrates the third type of resilience outlined by Handmer and Dovers [40]: *openness and adaptability*. It is characterized by the ability to adapt to the consequences of change and uncertainty, rather than resist them. The underlying structural causes of the problem are identified, the options are explored, and basic operating assumptions are fundamentally challenged and changed. An openness to radical change to social structure and institutional arrangements can lead to a redistribution of power, address the root causes of vulnerability, and allow for maximum flexibility in dealing with the threats and surprises. The potential negative features of this strategy include loss of optimizing capacity and greater chance of maladaptive change. A well known example of this type of is Durban, South Africa where the city has integrated long-term strategic planning and climate change mitigation and adaptation [86].

Handmer and Dovers' typology of resilience [40] provides a framework for analyzing the continuum of strategies between stability, marginal adjustments, and profound change. It highlights the constraints and opportunities that institutions may face in responding to global environmental change that affects their ability to deal with surprise. This framework is useful for considering the policy alternatives and strategies for dealing with such a complex global phenomena as climate change and its local impacts. It could aid the process of decision making under conditions of uncertainty by explicitly acknowledging the components of the systems that should be maintained as is, changed at the margins or changed qualitatively. As an example of this, consider Sorsogon City, Philippines (Text Box 1), which is one of the UN-Habitat's Cities in Climate Change campaign cities. This campaign aims to strengthen the response of cities and local governments to climate change. It brings together local and national governments, academia, NGOs, and international organizations to alert cities to the action they can take to respond to the climate change challenge. Policy dialogue and change, tool development and application, piloting mitigation and adaptation measures, and knowledge dissemination are among the key components of the program [104]. As the Sorsogon City, Philippines, example shows, the majority of the climate change strategies applied at the urban level are a mix of the three types of resilience: while the sea wall will still be rebuilt (resilience Type 1: Maintenance of the status quo), a new level of awareness of the risk exists institutionally and among the citizens (resilience Type 2).

While the fundamental issues of slums will not be addressed, the symptoms of potential disaster will be alleviated—a new building technique will be applied in the informal settlements (resilience Type 2). The fact that potential relocation is being addressed could be attributed to resilience Type 3 if the existing power arrangements would be redistributed in the consultation process and long-term development goals such as poverty reduction would be addressed. The role of equity and distribution of power and its impact on the resilience of the cities to climate change needs to be further examined.

12.6.1.2 Resilience-Resistance-Transformation Framework

Text Box 1 Sorgoson City

Sorsogon City is tucked between the Pacific Ocean and the South China Sea on a small strip of land in the Typhoon belt in the South of Luzon Island in the Philippines. This low-lying rapidly urbanizing centre is particularly at high risk to tropical cyclones and storm surges, extreme rainfall, flooding, increased temperature variability and seal level rise. Prevalence of poisonous algae in Sorsogon Bay is attributed to climate related changes. The main protection from storm surges, a seawall, was largely destroyed during 2006 typhoons. Lack of disaster risk reduction policies and infrastructure combined with low level awareness about climate related risks among local population and a general public that has limited knowledge about climate change related risks combined with a high percentage of informal settlements and high poverty rate (43% of the city population), makes this city particularly vulnerable to changing environmental risk.

In August 2008, the city launched a climate change initiative, championed by the mayor. Prior to that, climate change was perceived as a global or national issue requiring limited action from the local government. A series of briefings were held to enhance the understanding of climate change and the importance of local action in addressing the potential impacts which has resulted in a commitment from the decision-makers. Since then an intensive participatory vulnerability assessment has been completed that will feed into the updated City Land Use Plan. Multi-sector city consultations defined critical actions to increase people's resilience. These include: incorporation of innovative climate resilient human settlements; changing building practices in the informal settlements with techniques that allow for taking down a house in case of a typhoon warning, and to reassemble it after typhoon. The city is also setting land aside for resettlement purposes and will be starting consultations with the affected population. Other measures range from developing institutional capacity to respond to changing environmental risk to Mangrove reforestation and active involvement of the business sector in providing green building technology and promoting risk-resilient communities. A new plan for seawall rehabilitation is on the way which will be built in an eco-efficient manner.

12.6.1.3 Resilience-Resistance-Transformation Framework

Pelling [81], by drawing on systems and political economy theory, develops a resilience-transition-transformation framework that echoes Handmer and Dovers' typology [40] and provides empirical evidence from Latin American cities. Pelling explores the complex relationship between cities and global environmental change and brings power to the center stage of this relationship. Pelling's resilience is concerned with the status quo: the aim is to use current risk management to protect the established distribution of power. Current inequality is the cost of this stability and the prospect of economic wellbeing this might bring. The author suggests that this is the dominant mode of adaptation where resilience and adaptation are becoming almost synonymous in the policy arena. This is closely related to Type 1 resilience, discussed above. Pelling's transition seeks to promote good governance through exercising the rights that exist in the law but are not routinely adhered to. Social movements demanding transparency in building standards following earthquakes comprise an example of this. These rights claims can create changes in the operation and vision of governance systems and create space for progressive incremental social change as part of the risk reduction process. Finally, transformation fundamentally challenges dominant regimes, political systems, and the distribution of power as part of the adaption process. This is the most costly form of adaptation, be it at the individual level or at the level of institutional regimes. Pelling [81] suggests that as pressure from global environmental change grows, increasing the social, political, and environmental risk gaps, transformation will become more prevalent. Pelling is not advocating any of the strategies, but rather provides a conceptual framework for emphasizing that the social thresholds are as important as physical thresholds for helping identify where established urban socioecological systems may experience collapse and renewal.

It could be suggested that the concept of resilience as originally conceived by Holling and colleagues based on ecology does include all three types of responses to changes. The four-phase adaptive cycle developed by Gunderson and Holling [36] described above clearly reflects these strategies during conservation, release, and reorganization stages. Pelling, however, makes a provocative argument that increasingly at the policy and decision-making level, resilience is becoming to mean resistance, concerned with maintenance of the status quo of established urban systems. Pelling also addresses key criticisms of resilience theory—the lack of empirical studies (particularly at the level of the city) and the inability to acknowledge the distribution of power and its implications for the functioning of urban systems.

12.7 Conclusions

The chapter established a research context for strategies to building in resilience in cities, by examining the interplay between environmental risk and institutional responses to change and uncertainty. In the first part of the chapter, the three main themes of climate change adaptation in the cities were proposed based on the review of the current literature of adaptation science: climate change as a threats amplifier, climate change as a needs magnifier, and climate change as an opportunity. While the first two themes dominate current research on adaptation, the third theme is less explicit, yet valuable for framing policy options. As the National Research Council Report [70] on Adapting to the Impacts of Climate Change suggests:

> …because knowledge about future impacts and the effectiveness of response options will evolve, policy decisions to manage the risk of climate change impacts can be improved if they are done in an interactive fashion by continually monitoring the progress and consequences of actions and modifying management practices based on learning and recognition of changing conditions [70].

Thus, understanding changing conditions is central to effective adaptive response. This chapter provided an analysis of various ways *change* has been conceptualized, with a particular emphasis on surprise. The analysis highlighted current institutional inadequacies in dealing with changing environmental risk and provided a critical analysis of frameworks for responding to change: from anticipation and resistance to diversification and resilience. As examples from both developing and developed countries have demonstrated throughout this chapter, governance mechanisms, urban planning, and management are key to increasing resilience in cities. Planning for resilience is about negotiating the contentious balance between stability and change. It is largely dependent on the previous decisions made and inertia in the built environment but at the same time it has to keep pace with the changing social fabric, from rapid urbanization trends to changing societal values. The framework provided here could support decision-making processes in cities in the search for unique, place-specific, climate change adaptation strategies that at the same time consider global constraints for increasing the resilience of urban areas.

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Chapter 13
Adapting to Climate Change—A Wicked Problem

A Road Map for Action

H. Karl, C. Curtin, L. Scarlett, and W. Hopkins

Abstract Adapting to climate change presents a wicked problem. The properties of wicked problems are described, followed by a discussion of how learning processes developed to address wicked problems are suited to tackling climate change issues. The authors propose to meet the need for integrated research across disciplines by establishing a Virtual Institute to develop a core curriculum on complexity and wicked problems. The chapter concludes with a roadmap for action to adapt to climate change.

13.1 Introduction

"Wicked problems" are those that cannot be solved by technology and science alone because they result from interactions of cultural, ecological, and economic phenomena [31]. Problems having wicked properties have no endpoint solutions. Rather, actions and decisions to address wicked problems confront tradeoffs, with better or

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worse outcomes depending on actions chosen. Indeed, there are no solutions to problems having wicked properties, only better or worse outcomes. Almost all environmental problems are wicked. The dynamics of coupled natural and human systems combine to present the perfect storm of complex, multifaceted problems; climate change is exacerbating these dynamics [7, 18]. In order to achieve sustainable social systems and ecosystems, it is necessary to tackle these problems. Effective adaptive governance [8] is the key to building viable responses to wicked problems because it is often not the problems that are intractable, but the responses, which generate unintended consequences and inflexibility, when dynamic contexts require adjustment and adaptation. The basis for tackling wicked problems is through collaborative decision making processes at multiple scales that range from the local to the multinational. These processes require political and social will to undertake the hard work of collaboration, and, particularly, to shape the institutions, policy tools, and science support that sustain collaborative action over time [10].

We must avoid rigid approaches to dynamic questions that lead to—as conservationist Aldo Leopold noted more than 60 years ago—"the sad spectacle of one obsolete idea chasing another around a closed circle" [28]. Adapting to climate change presents a wicked problem. Human activities are influencing the climate in unprecedented ways in earth's history. Climate change is among the greatest challenges facing societies. Although it is a global phenomenon, it affects regions and localities in different ways. Anthropogenic activities have altered the natural climate system. Changing climate, in turn, alters human activities. This feedback loop is non-linear and effects are amplified in unknown ways that may lead to unexpected tipping points both in global climate and viability of societies. Societies must find ways to adapt to changing climate to sustain social systems. Human systems are coupled to, and indeed dependent upon, natural systems, requiring climate change research that integrates studies of both systems. Societies need to apply knowledge about these systems and their interactions to resource management, infrastructure, and other community decisions.

13.2 Properties of Wicked Problems

Brown [5] has succinctly laid out the properties of wicked problems relevant to policy decisions and social-ecological systems:

- Wicked problems evade clear definition. They have multiple interpretations from multiple interests, with no one version right or wrong.
- Wicked problems are multi-causal with many interdependencies, thereby involving tradeoffs between conflicting goals.
- Attempts to address wicked problems often lead to unforeseen consequences elsewhere, creating a continuing spiral of change.
- Wicked problems are often not stable. Problem solvers are forced to focus on a moving target.

- Wicked problems can have no single solution. Since there is no definitive stable problem, there can be no definitive resolution.
- Wicked problems are socially complex. Their social complexity baffles many management approaches.
- Wicked problems rarely sit conveniently within any one person, discipline, or organization, making it difficult to position responsibility.
- Resolution of wicked problems necessarily involves changes in personal and social behavior, changes that may be strongly resisted or encouraged, according to circumstances.

Wicked problems are sometimes considered intractable. Yet they are only intractable if one expects a discrete and one-time solution. The nature of wicked problems constantly evolves through time, because both natural and human systems are dynamic and interact in complex and non-linear ways [33, 34]. One must be attuned to their emerging properties and adjust. Environmental challenges are occurring at multiple scales, and it is the cross-scale interactions that make them so intrinsically hard to address [17, 18]. Thus, one cannot approach solving a wicked problem with a specific outcome, or even a specific scale in mind. Rather, wicked problems require decision processes that use feedback loops, iterative learning, and action adjustments (e.g., triple-loop learning processes). The solution to wicked problems is not an endpoint, but iterative and adaptive decision processes in which actions are altered and adjusted in response to the emergent properties arising out of the dynamic and complex coupling of natural and human systems; in other words, wicked problems require ongoing processes and not discrete decisions or solutions. This is the role of relevant and well-designed science coupled with local knowledge to test assumptions and generate the necessary feedback loops that inform policy and facilitate adaptive processes [2, 12]. The dynamic context of wicked problems requires the design, fostering, and support of adaptive decision-making processes, governance frameworks, institutions that strengthen opportunities for citizen collaboration, and the generation and use of science and relevant technical and experiential knowledge necessary for reflective practice and more effective stewardship and design.

13.3 Adapting to Climate Change by Tackling Wicked Problems

Climate change presents a complication and an opportunity—an opportunity to design and implement institutions that are compatible with tackling wicked problems. These institutions must link practitioners, academics, and managers to develop new ways to approach environmental problem solving. These linkages require institutional designs that respect equally the lessons from large and small systems, and the knowledge of academics, local practitioners, and federal policy makers and others alike in a science-based framework (e.g., questions or approaches are testable and data is collected on practices). Existing decision-making processes, legal frameworks, and institutions developed in the context of a stable climate and with the presumption that future climatic patterns would reflect those of the recent past. That context no longer applies. The National Research Council [11] report, *Informing Decisions in a Changing Climate*, asserts:

> Decision makers need…new kinds of information, as well as new ways of thinking, new decision processes, and sometimes new institutions, to function effectively in the context of ongoing climate change.

These dynamics of tackling wicked problems requires not a single monolithic organization or institute, but rather the synergy that can only come from a diverse yet integrated network of researchers and practitioners with a variety of strengths and assets. The synergy between academics and practitioners is crucial to linking theory with practice across a range of scales using a combination of learning and governance that link place-based perspectives. At the intersection of governance and learning are adaptation processes that link political and social systems.

Over the past decade, and—especially—within the last 5 years, researchers investigating social-ecological systems are realizing that governance processes and institutions are important aspects of sustainability. That is, sustainability concerns social, economic, and environmental outcomes and the governing processes through which people participate in decisions that affect them [7, 8, 11, 24, 29]. Folke and others [16] point out:

> Management power and responsibility should be shared cross-scale, among a hierarchy of management institutions, to match the cross-scale nature of management issues.

Increasingly, natural resources and urban systems are being managed through collaborative cross-jurisdiction, cross-scale, and cross-sector networks. How these collaborative governance regimes are performing, what kinds of adaptive capacity they are building, and how they can be enhanced needs to be a major focus of research.

With respect to the above, the field of collaboration and consensus building [10, 21, 36, 38] and the recognition of the importance of local and indigenous knowledge [1, 15] are especially important. The methods suggested in the most recent work [6, 30] for tackling wicked problems are essentially the best practices of participatory and consensus-based decision making, which include joint fact finding [14], worked out over decades through collaborative learning [4, 13] applied within a complex adaptive system context. "Effective decision support needs to begin with collaborative problem definition, including all the parties involved, and to support interactions and learning among them" [11].

To be successful, learning processes must nurture innovation that retains the necessary adaptive capacity [37]. Double or triple-loop learning promotes "learning to learn" [3, 32], where the system is designed from its inception in order for participants to learn more effectively and apply the lessons to practice (Fig. 13.1). This approach has been successfully used in corporations for decades [35]; we propose here to develop the learning networks that allow for cross-scale approaches to innovation and adaptation in coupled human and natural systems.

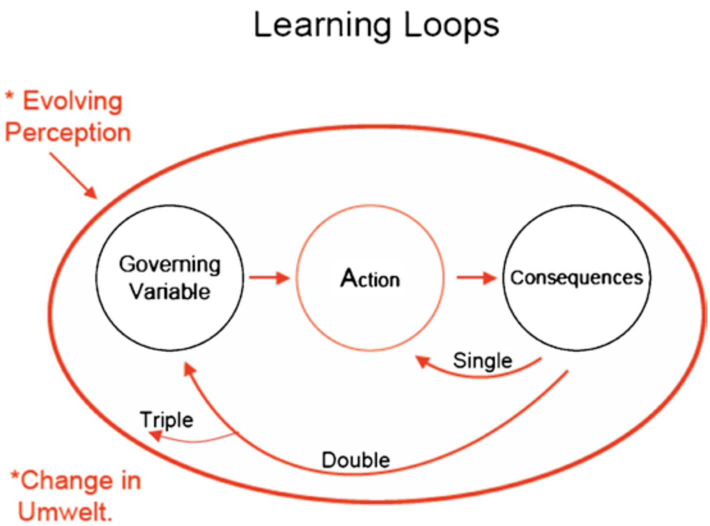

Fig. 13.1 (After Curtin [12]). Learning loops contrast different abilities to obtain knowledge and profit from experience. Whereas single-loop learning asks what is wrong and how to correct it, and double-loop asks why it is wrong and how to prevent it, triple-loop learning seeks to transform the bounds of decision making: are we even asking the right questions at the right scale? The purpose of this network is to have transformative learning or change in *unwelt* (world view) by addressing complex problems through networking across scales and institutions

Addressing the interaction of, and creative tension between, learning and governance, requires a novel network of academics, federal policy makers, agency scientists, nonprofit scientists, and citizen practitioners. This diversity of perspectives enables the exploration of decision-making processes and governance regimes to tackle wicked problems and undertake the action research to put in place decision processes and governance regimes to support collaborative and adaptive decision making (Fig. 13.2).

13.4 Need for Integrated Multidisciplinary and Interdisciplinary Research

To underscore both the urgency and challenges of developing multidisciplinary research teams to address coupled natural-human systems, consider a passage in the National Research Council [11] report, *Informing Decisions in a Changing Climate*:

> … [I]t is critical to build multidisciplinary and interdisciplinary teams whose members interact and work together to better integrate data for use by decision makers. … Many well-documented challenges exist, including overcoming the transaction and opportunity

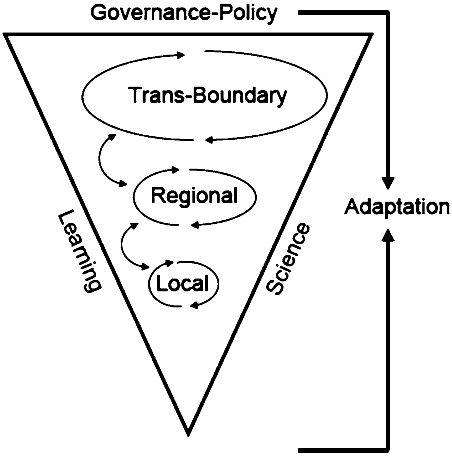

Fig. 13.2 (After Curtin [12]). Consider one learning model. Concentric circles depict both the discrete projects on the ground and the hierarchy of learning and governance. The inverted triangle shows the growing size of the number of interactions and complexity as we proceed up in scale from local (community level) to regional (multiple communities), to trans-boundary (multiple continents/countries). Governance is at the top of the triangle because it influences both effective learning and science, particularly the ability to test for and learn from success and especially from failures. But effective governance cannot exist without effective learning and science (and vice versa), such that a creative tension exists between the three. The grounding in real systems coupled with local knowledge, integrated with governance, learning, and science, leads to adaptation

> costs associated with cross-discipline collaborations, attempting to launch multidisciplinary efforts within organizations that reward discipline-based work, training the needed workforce, and enabling scientists to develop careers in interdisciplinary science. This need has long been recognized with regard to research on human-environment interactions… A particular need is for development of the scientific workforce at the interface of the environmental and social sciences.

The call for multidisciplinary and interdisciplinary research to investigate environmental systems is not new, dating at least to preliminary work[1] in adaptive management from the early 1970s [19]. Others have echoed this call repeatedly since that time [11, 26, 29]. For example, as recently as 2006, Neal Lane in his *Science* editorial, “Alarm Bells Should Help Us Refocus,” states that to meet the challenges of a rapidly changing world we must engage:

> … the nation’s top social scientists, including policy experts, to work in collaboration with scientists and engineers from many fields and diverse institutions on multidisciplinary research efforts that address large but well-defined national and global problems [25].

[1] Indeed, one can find strong arguments for multidisciplinary research and the intertwining of social and ecological systems in the work of Aldo Leopold in the 1930s, culminating in his *Sand County Almanac,* published in 1949. The point is not to track down the earliest reference to such work, but to understand why it is called for repeatedly and yet not become routine, especially substantive work between the biophysical and social sciences.

To increase the number of scientists with these capabilities, the NRC has encouraged institutions of higher learning to "improve the cross-disciplinary training of natural and social scientists … and [to create] programs of training for 'science translators.' Science translator training programs "should include exposure to the natural and social sciences, policy development and implementation, and conflict management and communication skills" [29]. Citizens such as those who comprise local collaborative groups are an important addition to this mix. Actually achieving an integrated, interdisciplinary approach is difficult. Many studies described as interdisciplinary in fact report their results as individual discipline papers in a compiled volume labeled an interdisciplinary study. Holling and Chambers [19] articulated why interdisciplinary research is so difficult: "…even if an ideal interdisciplinary research activity could be mobilized to produce a better mousetrap, no one would beat a path to its door." Universities can be effective environments for research, but they are not institutions that implement the results of that research. Government agencies can formulate policy, but are too fragmented to implement policies with interdisciplinary and cross-issue characteristics. Holling and Chambers point out that neither of these institutions "…alone can bridge the gap between abstraction and rigor on the one hand, and policy formulation and implementation on the other." To bridge the gap, it is necessary to establish a dialogue among citizens and these institutions.

Consider how societies are responding to climate change. Many of these efforts focus on scientific and technological remedies and not the process by which theory becomes practice. Mitigation has been more about new technologies than it is about altering economic and social institutions and actions. Adaptation (which should include mitigation) has gained increasing attention over the past decade. Many local, state, and national governments have published adaptation plans. Yet few have taken steps to implement adaptive strategies, and most continue to focus on mitigation. Climate change (and management of ecosystems and natural resources) is not solely, or even primarily, a scientific and technological problem—it is a social and political problem. The research community has not sufficiently focused on understanding the dynamics of the coupled social (human) and climate change (natural) systems. Instead, much climate research continues to focus on technological solutions. Now, many researchers are striving to develop geo-engineering solutions to alter the climate. Human communities have tried to engineer ecosystems (e.g., the Everglades, the Missouri-Mississippi system) with adverse, sometimes disastrous results. Engineering of the atmosphere is also likely to result in unintended consequences. Yet risky engineering options continue to receive attention while less focus is paid to the social and political institutions that shape how communities engage in decisions; how relevant information is generated, communicated, and used; and how incentives and methods of accountability affect choices.

Certainly, the use of scientific and technical information, models, and other tools enhance societal understanding of natural and other phenomena and help in problem solving. However, these tools should be aids to a deliberative process and not intrinsic ends in themselves. In reality, the exact opposite is often true: effective tools and relevant science often emerge as an outcome of viable social process and governance [12]. Thus, social process affects science much more than science and technology influences social outcomes. Yet climate adaptation and mitigation strategies have not generally centered on deliberative processes and their intersection with technical and scientific knowledge and tools. This technical and scientific knowledge and related tools can be applied to addressing climate change and its effects on natural resources and human communities; however, communities articulate their values and priorities, identify challenges to fulfilling those values and priorities, and determine how to address those challenges through social and deliberative processes. Much of the pioneering work extends back over 30 years to the late 1960s and 1970s when researchers sought to capitalize on the imperative of the environmental movement and the lessons from such social and ecological experiments as the Great Society and Green Revolution [9]. With many of the basics in place by at least 1980, the question remains why four decades of application and experimentation have not been more successful.

13.5 Adaptive Processes: A Research Framework

Research relevant to implementing adaptive processes to climate change should be undertaken within a scientific framework by asking testable questions. Until recently, most guides and discussions on adaptation to climate change have presented concepts and generalities, telling us what to do but not how to do it [7, 8, 12]. Here we undertake the broader question of how to develop the preconditions for effective adaptation.

An overarching goal for achieving sustainability is to couple the resiliency of natural systems with local knowledge and scientific and technical innovation in order to develop resilient social systems and collaborative governance processes that can adapt to the emergent properties of environmental change. Below we put forth important questions and suggest project designs to answer them. In a subsequent section we provide examples of the types of projects that could be undertaken following our project design.

13.5.1 Meta-level Questions

The meta-level questions that should be addressed include:

- Are current institutions and governance structures adequate to deal with the impacts of humans on the environment now aggravated by climate change?
- Are new institutions and forms of government necessary to achieve sustainability in a changing climate? If so, what forms should these take?
- Are there emergent models that show promise for integrating decisions about natural and social systems that better coordinate actions across intersecting and interconnected issues and scales of complexity?

13.5.2 Project Design: Sustaining Ecosystem Function in the Face of Environmental Change

Across a hierarchy of three scales and focusing on water issues, consider one example of a paired analysis of discrete wicked problems. At the international/transboundary level, such a research project could contrast sea level rise and flood control in the U.S. and Netherlands with a focus on Amsterdam and federal policy in the U.S. At the regional level, the project could contrast forest management and climate change amelioration in the Sebago Lake Watershed and towns in Maine, and the Taunton River Watershed and counties in Massachusetts. At the local scale at Eastport, Maine, and North Haven Island, Maine, resilience could be examined through a focus on the recovery of near-shore fisheries, how to increase near-shore diversity to increase the buffering capacity of the systems, local response to sea level rise, and how to develop food and energy security in these remote rural communities and contrasting that with work on the effect of water and land use strategies in St. Johns River Basin in Florida.

Using our project concept, we intentionally do not define the precise project questions because the whole point of the project design is to have joint project development to collaboratively define the problems and potential solutions [19, 21, 35]. At each scale, students and researchers would begin by engaging practitioners, citizens, and resource professionals in defining what they believe are the most important parts of the system and feeding this knowledge back into the system to design approaches to test and verify this understanding before developing approaches that are "as simple as possible, but no simpler" (Gunderson, Holling, and Light [17], paraphrasing Albert Einstein), essentially following Donella Meadows' approach [27] of finding those levers in a system that have the biggest influence on function. In seeking to determine meaningful and durable results, the project design attempts to address three common questions that are simple to ask but often extremely hard to answer:

- Are we working at the right scale?
- Are we working in the right system?
- Are we asking the right question?

From this context flow solvable approaches to complex problems. A research team composed of academic researchers and practitioners who represent a broad range of disciplines and fields functioning as an integrated team could address both theoretical and pragmatic questions. For example, an academic scholar could help define the theoretical questions, an active or former high-level federal policy maker could help address the principal pragmatic barriers at the national level, and a practitioner at the community level understands the complexities and interactions of local systems. Such an integrated team, as represented by the authors of this chapter, for example, could reframe the approach to climate change adaptation and potentially develop a workable decision-making process.

13.5.3 Education as a Unifying Network Element—A Collaborative Institute and a Core Curriculum

More than a decade ago, in her Presidential Address to the Annual Meeting of the American Association for the Advancement of Science, Jane Lubchenco [26] asserted, "Urgent and unprecedented environmental and social changes challenge scientists to define a new social contract." Under this contract, scientists are expected not only to do the best possible science but also to produce "something useful." Lubchenco's challenge, in one form or another, has been issued repeatedly over the past decade. Yet, with some exceptions, scientists and decision makers, in academia and agencies, function in essentially the ways that they have always functioned.

Educating students in the processes and approaches that we propose is critical to building the capacity in universities and agencies to foster and sustain the institutions necessary to tackle the wicked problem of climate change. One educational model is that of a Virtual Institute to develop and adapt a core curriculum on complexity and wicked problems. The core curriculum would use online and distance learning modes for core course delivery, with online certification of completion similar to that used to certify the human subjects training required for social and behavioral research. All students would complete the core training before beginning fieldwork. The point here is to develop coherent approaches to adaptive practices that can be tested, evaluated, and modified based on experiences in the field. The broader we reach for diversity of academic disciplines and the greater scale integrations we attempt, the greater the need for an integrated core agreement on the basics of thinking about and addressing wicked problems.

13.5.3.1 Student/Local Practitioner Cooperation

Within a Virtual Institute context, to help build the capacity for climate adaptation in society at large, students would work with community groups to extract local knowledge and lessons learned by the community group in dealing with complex problems such as fisheries restoration and developing energy alternatives to fossil fuels.

Student interviews with local participants would give students insight into the realities of community life and processes and provide local participants access to the scientific expertise of the students, while creating a shared learning experience in collaboration for all involved. Students would return to their home institutions and share findings and experiences with senior researchers at the Institute and companion institutions in the network. This learning process is another important means by which to develop learning feedback loops in the network.

Based on the initial fieldwork contacts, community groups would negotiate with the Virtual Institute as to the community projects, academic disciplines, and student skill sets that would be appropriate for the next step: a significant undertaking that would use local and scientific knowledge in the persons of community residents and

Institute Fellows in a collaborative manner to learn how to increase community resilience in the face of complexity and dramatic change.

Areas of interest include:

- Continuation of existing efforts, such as further developing sustainable local fisheries
- Consideration of how large-scale phenomena such as sea level and sea temperature rise, extreme storm events, and ocean acidification have and might produce local effects, such as effects on commercially important fish species, or destruction of local marine infrastructure (wharfs, bridges, causeways)
- Opportunities for continued local development away from reliance on fossil fuels, such as generation of electricity using tidal power and offshore wind

While students with expertise in the biophysical sciences associated with climate change effects will obviously be useful, so would a Virtual Institute need access to the disciplines best suited to technology transfer and extension outreach, such as geographic information systems specialists, anthropologists, educators, web designers, and digital imagers. Additionally, the Institute would need students in the fields and disciplines of social science, political science, engineering, urban planning, and landscape planning.

Science and policy cannot operate independently of values in making decisions about complex and contentious environmental policy issues. It is essential for students to have a firm understanding of ethical behavior and values and to have built the capacity to translate that understanding into the everyday practice of research and management [20, 22, 23].

13.5.4 Examples of Specific Potential Action Research Projects

Tackling wicked problems does not require more theory development; it requires institutional development and action on the ground. However, as action unfolds within a research context, new theory will emerge that can be tested in practice. Below we provide examples of projects discussed with participants[2] at this workshop and with other colleagues[3] that could test the questions posed above and that could help develop the processes and institutions that will support adaptation to a changing climate.

[2] James Jones, Igor Linkov, and Myriam Merad.

[3] Keith Robinson, U.S. Geological Survey; Juan Carlos Vargas-Moreno, MIT; Steven Traxler, U.S. Fish and Wildlife Service; Eric Walberg, Manomet Center for the Conservation Sciences; Wouter Jonkoff, TNO, the Netherlands; Olga Ivanova, TNO, the Netherlands; Lisette Stahl, University of Florida; Wendy Graham, University of Florida; Paul Kirshen, Battelle Institute; Jessica Cajigas, New England Interstate Water Pollution Control Commission).

As stated earlier, local institutions play an important role in monitoring and responding to ecosystem change, but in order to be effective they must be connected to regional and national institutions in a way that permits coordination as well as flexibility, adaptability, and resilience. Thus, our project design, using the model presented here, would provide for researchers, citizen practitioners, and students working on each project to meet periodically to integrate what they are learning to move toward designing new institutional arrangements to more effectively tackle wicked problems. The following discussion presents a sample of interlinked local, regional, and international action and associated research.

13.5.4.1 Local

A

The wicked problem: On the coast of Maine, decline in fisheries and increases in storm intensity and projected sea level rise are becoming increasing issues. The core wicked problem is restoring ecological and social resilience back into these systems, while building the adaptive capacity to respond to sea level rise.

The process: Building local ecological and social capacity through community-based fishery restoration and monitoring, coupled with more awareness of sea level rise and more effective town planning. This is done primarily through the efforts of local community resource centers including the Cobscook Bay Resource Center and the North Island Science Collaborative. These efforts seek to engage the community through education, community science and restoration programs, and raising awareness of education of town governments.

Outputs: Specific output and outcomes involve developing more effective coupled restoration, redevelopment, and proactive planning. Fisheries restoration currently underway—of shellfish in Eastern Maine and anadromous fish in central Maine—provides an assay of the system recovery to see how much residual resilience is left in the system following the fishery collapse. The success of these restorations not only aids the local economy, it provides insight into the system's capacity to rebound socially as well as economically. In both systems, local marketing systems are forming better linkages to markets. At the same time, mitigation of potential sea level rise can occur at the local level through more effective modeling of potential effects and town planning. These actions would be documented in popular articles in the local press such as *The Working Waterfront*, journals, and documentaries.

Outcomes: The success of local governance coupled with science would be measured through scientific studies of the rebound of fisheries such as those already underway at Antioch University. While this consortium of institutions can provide additional sea level rise planning expertise, an additional measure of success is the extent to the local effort could profit from and apply the Dutch experience at the international level to community and town planning at the local level in Maine.

Project: A network of local community-based science and research programs in Cobscook Bay in Eastern Maine, and Penobscot Bay in central Maine, provide a contrast of rural communities. This system displays an immense complexity of coastal systems at the interface of marine and terrestrial environments and also has well developed community-based science and resource management programs. A century of over-fishing has left an extremely simplified marine ecosystem. While lobster fishing is lucrative, it is unlikely to be sustainable, leading to a trap in which perverse incentives lead to a continued cycle of increasing social and ecological simplification and brittleness. In our hypothetical project, initial work would include monitoring recovery of fish restoration programs, developing community outreach and engagement in the fisheries restoration and a broader range of marine monitoring efforts, and conducting analysis of potential impacts of sea level rise coupled with studies already completed in other parts of New England.

B

The wicked problem: Developing socially acceptable, ecologically protective water and land use management strategies that are robust across possible future climate and population scenarios in the St. Johns River Basin (SJB), Florida, presents significant challenges. The geomorphology of the coastal river basin—together with the dynamic coupling among the groundwater, river, and wetlands systems—and the growing population centers around Orlando and Jacksonville, make the region particularly vulnerable to climate change and sea level rise.

The Process: Addressing these issues requires stakeholder scenario planning and integrated climate, land use, hydrologic, and ecologic modeling at the river-basin scale. The process would need to engage stakeholders (public, private, and civil leaders; water resource managers; utilities; and academics) to explore alternative futures for growth policies and regulation under a variety of climatic, sea level rise, population growth, and land use scenarios.

Outputs: Participants would develop a range of scenarios to aid the collaborative decision process. A guidebook describing the process could be produced to aid those who might want to undertake a similar process. Journal articles could also be produced to communicate research insights and findings.

Outcomes: There is considerable interest on the part of water resource managers, and considerable opposition on the part of environmental advocacy groups, in using surface waters of the SJB as an alternative water supply. A consensus-seeking stakeholder process, which would become a routine process for making decisions in the SJB, could help resolve conflicts associated with water supplies.

Project: The SJB is a humid, low-relief watershed where increasing freshwater demands and land use changes, as well as concern over potential impacts of climate change and sea level rise, are causing stakeholders to voice concerns about ecological impacts of current and future water supply plans. In the SJB, groundwater from the Upper Floridan Aquifer has been the traditional source of freshwater for agricultural, industrial, and public water supplies. Future water needs cannot be met by continued reliance on groundwater without unacceptable impacts to the region's wetlands, lakes and springs. St. Johns River Water Management District (SJRWMD), the regional water management authority, has capped future groundwater withdrawals at 2013 demand in the region to prevent harm to water resources and natural systems. However, increasing dependence of public water supplies on more dynamic surface sources (versus more slowly varying groundwater sources) will make water management systems more vulnerable to changes in climate patterns and sea level rise, and could produce unacceptable ecological impacts in the river and floodplain wetlands.

13.5.4.2 Regional

A

The wicked problem: Developing and implementing climate change adaptation measures against the backdrop of the complexity at the landscape and landowner scales presents challenges in watersheds in Eastern Maine and Massachusetts.

The process: Federal, state, and local government partners and landowners could partner to identify and implement the best climate change adaptation measures. The lessons learned through this process would be synthesized into sector-specific guidance.

Outputs: Climate change adaptation plans would be developed for each of the sites, along with analysis of the stakeholder process and policy recommendations.

Outcomes: The project design would aim toward development of an enduring collaborative stakeholder process and institutional arrangements to inform decisions in a changing climate.

Project: The Manomet Center for Conservation Sciences is currently involved in a multiyear climate change adaptation effort. The project is focused on the development and implementation of climate change adaptation plans at both the landowner and the landscape scales. At both of these geographic scales a broad spectrum of stakeholders and interests will be involved. The complexity at the landowner scale is the result of the interaction of economic, ecological, policy, and social spheres. The complexity increases at the landscape scale with the addition of multijurisdictional interactions. Students could use the climate change adaptation program at the Manomet Center for Conservation Sciences as a framework for the exploration of challenges associated with maintaining the viability of ecosystem services under the stress of climate change.

B

The wicked problem: Monitoring water resources across multiple jurisdictions to ensure water quality and sustainability in a changing climate is a growing challenge for many regions.

The process: Working with federal and state government partners and a regional interstate coordination agency to implement a regional water monitoring structure could assist communities in effectively and efficiently measuring how climate changes impact the quality and quantity of water resources throughout New England.

Outputs: This regional project would assess recent and current routine water monitoring activities in New England by state and federal agencies, provide a gap analysis of available water data relative to critical water management and planning issues in the New England region related to climate change, and describe the institutional barriers to regionalization of water monitoring activities.

Outcomes: The project would result in a New England-wide regional monitoring strategy to address how climate changes are affecting the region's water resources. In addition to describing the data and science needs associated with this monitoring strategy, institutional and financial barriers would be explored. The New England region is ideal for a regional monitoring focus because of the number of interstate river basins, and similar nature of the landscape, water stressors, and potential impacts of climate change on water quality and quantity.

Project: Partners for such a project could include, for example, the U.S. Geological Survey (USGS), New Hampshire/Vermont Water Science Center, and the New England Interstate Water Pollution Control Commission (NEIWPCC) to look at critical issues of a changing climate on water resources and their management in the New England region. These issues would be linked to a strategy for monitoring the quality and quantity of waters and incorporate input from all the states and federal partners in the region and the results of recent meetings/conferences that have addressed this issue recently. This effort would be coordinated via an active climate change workgroup operated by NEIWPCC. Current monitoring practices are highly variable from state to state, leading to inconsistencies in our understanding of water resources across New England. The end goal would be the development of a New England Climate Effects Water Monitoring Strategy to oversee and coordinate across states. If successful, this approach could be used to address how regional monitoring strategies could be beneficial to other vexing water management issues in the region.

13.5.4.3 International and Transboundary

A

The wicked problem: Setting environmental policy and making natural resource management decisions involve contentious social, political, scientific, and technical issues.

The process: Working with federal, state, and local government partners and citizen practitioners, participants would implement concepts of adaptive governance, networked governance, and collaborative governance.

Outputs: Journal articles and working papers would be used to document the results of experiments in implementing new governance regimes; workshops and conferences to address the theory and practice of making decisions within the context of new governance regimes would provide a means of sharing results.

Outcomes: The project would result in new institutional arrangements or governance models to deal with wicked problems and implement sustainable practices for managing ecosystems and social systems.

Project: New governance regimes—such as adaptive governance, networked governance, and collaborative governance—are a key to addressing wicked problems and sustainability. Opportunities exist to build upon insights developed through efforts of groups such as the federal Interagency Cooperative Conservation Team (chaired by Lynn Scarlett during her tenure at the Department of the Interior) and to work with willing federal agency partners to explore how they can move forward with participatory decision-making processes. Coordinating partners could include agencies such as the USGS and the U.S. Fish and Wildlife Service (USFWS) on issues in New England.

B

The wicked problem: Protecting communities from more frequent and longer duration floods caused by changing climate is a common theme as nations and communities grapple with the effects of climate change.

The process: A project to work with communities through a collaborative process to consider tradeoffs among engineering solutions, restrictions on dwelling in flood zones, and "living with nature" could help them address these issues.

Outputs: Such a project would result in multi-agent-based simulation models, spatial computable general equilibrium models, journal articles, and guidelines for best practices.

Outcomes: Outcomes would include improved quality of flood prediction projections, more equitable insurance policies, urban and social planning in harmony with natural processes, better understanding of cultural contrasts.

Project: Water resource management is a critical global issue; how nations and communities respond to it will be critical for sustainability given a rapidly changing climate. One project concept would assemble partners to work with TNO, the Netherlands' applied science organization, on the Dutch Knowledge for Climate Change Programme[4] on the development of decision support tools focused on the effects of floods and changing practice to how communities respond to the threat of floods. The goal of the project would be to model flooding to understand the effects on transportation patterns, businesses, housing, and agriculture. The study could be paired with a similar study in New England in cooperation with the USGS and National Weather Service.

[4] http://www.climateresearchnetherlands.nl/templates/dispatcher.asp?page_id=25222734.

13.6 Road Map for Action to Adapt to Climate Change

In this chapter, we have not only discussed conceptually what needs to be done for societies to adapt to climate change but also provided a conceptual project to illustrate how to undertake the experiments to develop and implement the institutions and capacity that would enable a collaborative and adaptive decision-making process. Most of all, adaptation to climate change requires a different mindset—acknowledging that the environment is the basis of sustainability and what people do socially, politically, and economically ought to be in harmony with a healthy environment. Our conceptual approach requires:

1. Developing an enduring network of researchers and practitioners to conduct research and take action on wicked problems.
2. Designing and putting in place processes to make collaborative learning routine.
3. Developing and testing new institutional arrangements to connect effectively local, regional, and national institutions that monitor ecosystems and their services and make decisions and regulate these systems in a social and political context.
4. Experimenting with and developing governance regimes that are flexible so that societies can adapt and increase their resiliency to changing climate and the emergent properties of the complex dynamics of coupled natural and human systems, and become sustainable.
5. Developing a core curriculum and training students in the classroom and in the field and through a Virtual Institute to deal with wicked problems. These students, as the leaders of the future, will begin the process of cultural and institutional change to enable sustainable societies and ecosystems as they spread into academe, and the public and private sectors.
6. Exchanging information across jurisdictions and nations to learn from each other. That which works in one political, social, and cultural environment might not work in another.
7. Raising awareness that we need to develop new processes by which we interact with each other, or more accurately, put in place and make routine those collaborative processes that have been developed but that are sparsely used. In order to adapt to changing climate we need to act collectively at all scales.

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Part III
National Security Applications and Needs

Chapter 14
National Security Perspectives on Addressing Instabilities Arising from Climate Change Impacts on the Environment

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Abstract Societal stability and the security of peoples can be threatened in subtle, complex, and profound ways by the effects of global climate change on the environment. Stresses due to climate change on the quality, quantity, and distribution of environmental resources accessible by nations and regional communities often multiply security threats. Active security concerns can become heightened in these conditions. New security issues have potential to emerge with mobilization of new or latent stressors. Contemplating science-based, plausible climate change futures that

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have potential for impact provides context for anticipating environmental security tipping points. Examination of historical environmental security risk analogs facilitates synthesis of knowledge for adapting to climate changes in ways that maintain and restore global environmental security conditions. National security agencies of governments equipped with this knowledge increase their potential to effectively identify, prepare, and apply measures to address climate change environmental issues on a timely basis to save lives, conserve natural resources, reduce international tensions, and build global trust.

14.1 Introduction

National security is concerned with protecting peoples from undue internal and external stresses that may disrupt the normal functioning of nations and states, enterprises, and citizens. It is built upon collaboration amongst multiple national and international agencies and organizations such as the military, civilian police services, emergency preparedness and response services, aid, and humanitarian organizations. National security is often underlain by fundamental inequities, within and between nations, in access to resources (e.g., financial and natural resources) and to decision making (e.g., people marginalized from decision making, or lack of transparency).

The contribution of climate change effects to national security concerns is a relatively recent concern of governments globally. The causes and impacts of climate change, as well as the differences in the capacities of nations and communities to respond, cope, and adapt, can be threat multipliers to national security [5]. Nations that are poised with the expertise, data, methods, and models to assess how changes in temperature, precipitation, and relative sea level may influence resident, transient, and emerging new threats to environmental security will be better prepared to proficiently manage for stability as challenging conditions are realized. Environmental security threats, climate change multipliers, and coping strategies are described in this chapter for consideration by nations and communities facing management of these issues.

14.2 Potential Climate Change Effects and Impacts on Environmental Security

National and global environmental security conditions will increasingly be subject to climate change effects. These effects, many of them indirect and some direct, are variable and uncertain in distribution, extent, and magnitude, both geographically and temporally. The U.S. National Security Strategy 2010 states:

> The danger from climate change is real, urgent, and severe. The change wrought by a warming planet will lead to new conflicts over refugees and resources; new suffering from drought and famine; catastrophic natural disasters; and the degradation of land across the globe. The U.S. will therefore confront climate change based upon clear guidance from the science, and in cooperation with all nations—for there is no effective solution to climate change that does not depend upon all nations taking responsibility for their own actions and for the planet we will leave behind [12].

Climate change effects undoubtedly will create environments where failed states do not independently recover good order and governance. Indeed, climate change along with extant environmental degradation, lack of institutional integrity, and global wealth inequalities could prove to be tipping points whereby the failed-state threshold is passed, particularly in Africa, South Asia, Micronesia, and possibly Latin America [8]. Within the Middle East, only Egypt and Iran are believed to have abundant and sustainable water supplies and future competing demands on scarce water resources—which could be reduced by a changing climate—may prove to be a threat multiplier in an already volatile region [2].

Troubling aspects for national security planners in developed nations such as those within the North American Treaty Organization (NATO) alliance is the high uncertainty that plagues future climate forecasting and modeling efforts. For example, some scenarios show the thermohaline conveyer in the Atlantic Ocean paradoxically returning northern Europe to a regional climate similar to the colder parts of the Holocene such as the Younger Dryas or the more recent Little Ice Age. This type of potential outcome reinforces the point that climate change may lead to diverse impacts, beyond expanded conflicts in poorly known corners of the developing world [9]. Higher demands and prices for energy, food, and other commodities could force lifestyle changes and limit economic growth in the developed world while fueling continued conflict and instability elsewhere in a negative feedback process.

Accordingly, from the global environmental security perspective, climate change influences can therefore be recognized as both a tactical and strategic set of issues that merit high-priority attention [4, 8]. For example, greater or more frequent coastal flooding in areas such as Bangladesh or portions of Indochina would require tactical deployment of amphibious and sealift assets of the U.S. and its allies to protect national interests and to facilitate disaster relief and humanitarian services [1]. Sea level rise would require complex strategic thinking about how infrastructure assets, particularly those from the U.S., are used and positioned worldwide [10]. Even modest sea level rise may render facilities on the island of Diego Garcia vulnerable if not wholly inoperable. This would deprive military forces of the U.S. and United Kingdom of their most important air and sea facility in the Indian Ocean region, which is critical to responding to military needs in south Asia and eastern Africa, as well as providing control over important sea lanes into the Far East. Increasing tropical cyclonic activity in southern portions of the U.S., where vital military installations are located, could impinge upon military readiness. Hurricanes Andrew and Ike, for example, seriously damaged installations in Florida, causing a substantial loss of capacity and function for many months [2]. Battlefield readiness similarly may become compromised from a human capital perspective if climate change leads to an increased and distributional spread of disease, particularly insect-borne tropical pathogens such as malaria or dengue fever both in domestic installations and overseas forward-operating areas [11].

Increasingly, climate change is being viewed by the national security community as an emerging, if not already present, security challenge that has potential to shape the time, place, and underlying causes of future conflicts. Regionally specific concerns arise for contemplation of international government actions in maintaining and restoring global environmental security:

- Adaptation of capital assets in environmental settings that are vulnerable to climate change effects, but yet not impacted
- International aid operations that must be planned for and conducted in response to climate changes that have taken effect
- National infrastructure rebuilding that must address climate change effects for near- to long-term sustainability

In order to describe the potential effects of climate change on global environmental security operations, potential concerns are catalogued on a regional basis based on an existing U.S. convention. The U.S. military is currently divided into six separate Combatant Commands (Fig. 14.1).

Table 14.1 provides a key to the acronyms of Fig. 14.1. According to the Intergovernmental Panel on Climate Change's (IPCC's) 4th Assessment Synthesis Report [7], each command can expect to experience some potentially significant tactical and strategic impacts arising from potential climate change effects (Tables 14.2–14.7).

Even in best-case scenarios, where global temperatures increase by no more than 2°C, increases in insect-borne diseases, losses or radical shifts in arable land and agricultural production, decreases in potable water, coastal inundation from sea level rise and potential mass migration of human populations are foreseen [2]. Referring to the 2010 Quadrennial Defense Review, Freier [6] stated:

> …the U.S. must rationalize competing visions about the certainty of future unconventional threats and lingering uncertainty about evolving traditional challenges. Doing so requires adoption of a new risk management defense strategy.

In *Implications of a Changing NATO* [3], a question was posed in the Multiple Futures Project (MFP):

> What are the future threats and challenges that could pose risk to the interests, values, and populations of the Alliance?

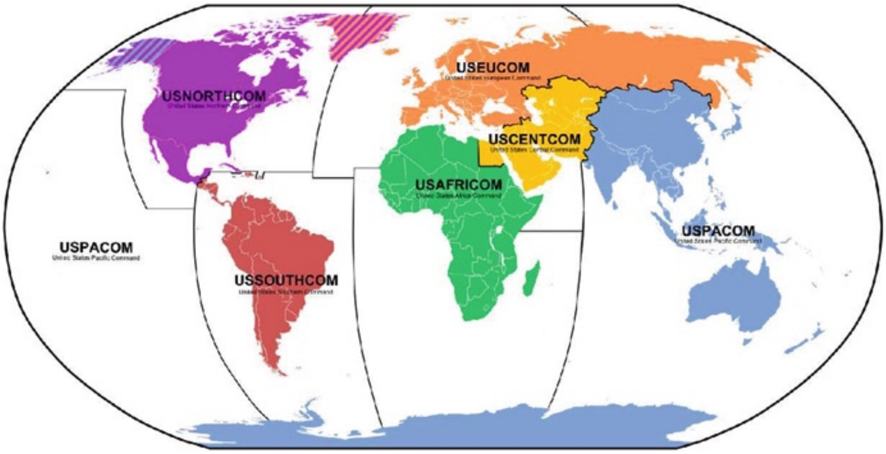

Fig. 14.1 U.S. combatant commands [13]

Table 14.1 Key to acronyms of Fig. 14.1

USNORTHCOM	U.S. Northern Command
USSOUTHCOM	U.S. Southern Command
USPACOM	U.S. Pacific Command
USEUCOM	U.S. European Command
USCENTCOM	U.S. Central Command
USAFRICOM	U.S. Africa Command

Table 14.2 Potential climate change (CC) impacts and effects, NORTHCOM

Potential impacts	Potential effects
Sea level rise	Flooding and increased storm damage resulting in loss of critical infrastructure
Permafrost thaw	
Altered precipitation and temperature regimes	Reduced terrain navigability and increased wetland formation
	Methane release from tundra decomposition and increased CH_4 emissions at higher rates than CO_2
Altered snowpack melt	
Loss of Arctic sea ice	Habitat changes, especially for anadromous fish species
	Increased risk of catastrophic fire events, changes in agriculture, and biome shifts (i.e., altered habitat and species distributions)
	Ocean acidification and reduced productivity, distribution, and species diversity
	Altered watershed hydrographs (i.e., expected water supply becomes vulnerable)[a]
	Increasing maritime operating area and associated requirements

[a]Landscape changes that provide more carbon inputs into the atmosphere such that additional global warming occurs.

Table 14.3 Potential CC impacts and effects, USSOUTHCOM

Potential impacts	Potential effects
Increased desertification (and aridity) leading to loss of arable land	Reduced food production—possibly stimulating mass migrations
Reduced water availability	Water shortages leading to increase local conflicts and possibly reducing hydropower generation
Altered precipitation and temperature regimes	Decreased plant and animal diversity, changes in distribution of disease vectors, significant losses of Amazonia rain forests, increases of catastrophic fires
	Ocean acidification and reduced productivity, distribution, and species diversity

Table 14.4 Potential CC impacts and effects, USEUCOM

Potential impacts	Potential effects
Sea level rise	Saltwater intrusion into aquifers and surge-driven flooding
Glacier retreat and decreased snow cover	Decreased water availability—which will destabilize the region
Decreased arable land	Food shortages and greater reliance on imports
Loss of Arctic sea ice	Ocean acidification and reduced productivity, distribution, and species diversity
	Migration
	Increasing maritime operating area and associated requirements

Table 14.5 Potential CC impacts and effects, USCENTCOM

Potential impacts	Potential effects
Increased desertification (and aridity) leading to loss of arable land	Reduced food production—possibly stimulating mass migrations
Decreased water availability	Increased local conflicts
Altered precipitation and temperature regimes	Reduced water availability, changes from semi-arid to almost complete Sahara-like conditions, and increased duration and frequency of storms
	Migration

The intent was to provide Alliance leaders with a broad set of ideas and information to use for future planning, presented as four plausible future scenarios that could be encountered by the year 2030. Since the question remains open for climate change effects, a limited research program was initiated through our study to collect additional ideas and opinions on the topic for Alliance leaders to consider.

Table 14.6 Potential CC impacts and effects, USAFRICOM

Potential impacts	Potential effects
Altered precipitation and temperature regimes	Continued Sahel desertification, placing agriculture and nomadic peoples at escalated odds, with continued savanna systems deforestation, possibly causing nomadic migration into central Africa, increasing its deforestation, biodiversity losses, and CO_2 releases
Declining quantity and quality of drinking water	Destabilizing local governments and mass migrations
Increased desertification (and aridity) leading to loss of arable land	Reduced natural resource productivity and threatened food security, particularly in sub-Saharan Africa
	Ocean acidification and reduced productivity, distribution, and species diversity

Table 14.7 Potential CC impacts and effects, USPACOM

Potential impacts	Potential effects
Altered precipitation, temperature, and tropical cyclonic activity regimes	Rice yields are projected to decrease in lowland areas by 40%, leading to food shortages
Increased flooding	Coral reef loss due to warming and acidification of oceans from CO_2 solubility will disrupt and alter aspects of fisheries
Sea level rise	Increases in mortality rates, losses of critical infrastructure, reduced terrain navigability
Glacial retreat and decreased snow cover in the Himalayas	Saltwater intrusion into aquifers and surge-driven flooding
Loss of Arctic sea ice	Decreased water availability—could lead to mass migrations
	Increasing maritime operating area and associated requirements

14.3 Climate Change Management for National Security

Management of these issues can be performed at a range of levels, considering basic principles and methods, depending on how much information and lead time is available to plan and adapt. Regardless of the amount of information available or that can be generated, in principle an objective, systematic, and consistently applied approach should be undertaken. Governments with relatively greater technical expertise and resources are in a better position to effectively and efficiently assess risks and manage uncertainties for guiding actions. The timeliness and robustness of actions taken will reduce the potential for future management regrets. Frequent and transparent communication to the populace by governments on environmental conditions and how they are being addressed is of great value to maintaining and restoring security. Useful principles and methods are elaborated upon below for conducting assessment and adaptation.

14.3.1 Objectives Establishment

Objectives must be identified for the exploration of the risks and consequences of climate change effects on environmental variables that impact the maintenance and restoration of societal stability and security. The objectives chosen have to be important to interested and affected parties, sensitive to climate change effects, and possible to model and assess as variable uncertainties. Objectives may be prioritized and will almost always require tradeoffs when being managed. Given inherent uncertainties and the degree to which they can be resolved—as well as competition among prioritized objectives—the key is not optimizing outcomes, but avoiding the disenfranchisement of peoples or business sectors to the point of stimulating destabilizing conflicts.

14.3.2 Systems Approach

A nation or regional community can be characterized as a system. Earth systems are comprised of natural assets and built infrastructure, which function to serve society. Each of these systems consists of interconnected elements or subsystems that combine to attain societal stability and prosperity. Systems are not isolated and interact with each other and the global climate (i.e., an open system), whether the interaction was planned or evolved randomly. System components and their boundaries may be defined based on physical characteristics such as geography, hydrology, landscape, utilization, and political subdivision. Functional process associations should be identified between these features at the appropriate scales.

Global and regional climate variables place stressors on earth systems, which may amplify existing threats or expose new ones. Adaptation is the property that allows a system to survive and maintain effective operation in a changing climate. Adaptation potential of a system can be characterized by the presence of available resources, as well as existing capacities and limitations in functional performance. Adaptation may be imposed through conscious planning and actions to set measures in place. Self-adaptation capability may also be present, which allows the system to sustain itself through external changes without additional management actions or infusion of new or different resources. Self-adaptation, or natural sustainability, is present when built infrastructure and societal activities are in synchronicity with natural systems and processes. This is a high-priority goal for any kind of natural system.

14.3.3 Modeling, Performance Assessment, and Adaptation

The roots of environmental security objectives may be identified through modeling. Modeling may legitimately take many different forms, from conceptual and qualitative to analytical and quantitative. Expert judgment based on available information is often useful in making initial determinations on which systems and processes are most important to model and how, considering available time, resources, and capabilities. It is strategic for the sake of timeliness and resource conservation to pool expertise to effectively identify specific methods, models, and data that can potentially deliver the highest value.

Uncertainties that cannot be practically modeled may be managed as uncertainties across a range of equally likely possible future conditions. Models of systems and processes should be developed and implemented to understand sensitivities in performance according to desired objectives across the spectrum of driving uncertainties. Potential reductions in stability and security should be identified to shape adaptations that respond favorably no matter which actual future is realized. In principle, adaptation strategies should be formulated and evaluated in consideration of uncertainties to:

- Avoid unintended consequences and catastrophe
- Possess characteristics of flexibility for further adaptation or reversibility in case of unintended outcomes
- Incorporate low-cost, high-value additional margins of safety (e.g., multiple lines of defense against adversity) for resilience against rare and extreme threats
- Minimize investment timelines
- Seek to exploit potential synergies for system integration and performance

Absent the expertise and resources to perform highly technical modeling, investigation of historical analogs with discussion and debate among subject matter experts may be an expedient and cost-efficient approach to identifying and synthesizing relevant information into useful assessment tools and products. Much of the uncertainty of climate drivers and environmental system/process variables may be resolved through this type of exercise, being relatively valuable and leaving relatively low residual potential for quantification via more formal, technical methods, whether for use by highly developed countries or those with limited capabilities. Working with natural systems and processes and adaptable strategies and measures may be sufficient to marginalize the value of using more detailed, expensive, and time-consuming modeling approaches. The less complicated the systems and processes, the greater this potential.

14.3.4 Collaboration and Communication

Interagency and intergovernmental collaborations to shape regions of concern about security maintenance and restoration are enablers of effective and efficient achievement, as well as strategic international relationship building to foster international trust. Collaboration for the sake of addressing climate change and adaptation needs often works best using a representative democracy model of the affected region, country, or group of people, regardless of the types of governance of the individual parties involved.

Nations should conduct public awareness activities to communicate the science of climate change effects and impacts to engender cultural transformation leading to good practices that reduce the need to operate in disaster-response mode. It is wise to perform frequent and transparent outreach to convey the challenges and successes of security planning and operations to address climate change and adaptation needs.

14.4 Conclusions

Potential future climate change effects have introduced additional uncertainties into the inherent complexities and unknowns of where, when, and how environmental security threats will have to be addressed by governments worldwide. The challenge nations now face is one of adaptive management to objectively maintain and restore societal stability. There is a need for effective model forecasting and adaptive management of environmental systems, considering multiple plausible futures. Adaptation strategically embraces the uncertainties of potential climate shifts by working with natural systems and processes in achieving resilient, sustainable conditions. International collaboration is necessary to undertake these difficult challenges. Communication about the science of climate change and ways to reduce the multiplicative potential of environmental security threats that are subject to climate change impacts is an enabler of cultural transformation to give momentum to realize these aspirations.

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Chapter 15
Climate Change, Scarcities, and the Resulting Challenges for Civil Protection

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Abstract In spite of political and public disagreement about the danger of ongoing and impending climate change, actual climate change impacts have been unambiguous. Managing climate risks presents challenges because of policy debate, limited resources, and the long timelines associated with climatic change and its effects. More effective approaches to address climate-induced risks should include integrating assessment of stakeholder concerns with environmental risk assessment and acknowledging the potential for civil disturbance. Nations must be increasingly prepared to include the impacts of climate change within civil defense and emergency response capabilities.

15.1 Introduction

There is seemingly irresistible scientific evidence both that the world's climate is changing and that anthropomorphic forcing—human activity—is a major influence on global warming.

Reports are published regularly, each one adding to the body of knowledge. A random look at publications in the month of October in recent years offers the Stern Review on the Economics of Climate Change (2006) (the Stern Review), the Garnaut

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Climate Change Review (2008) (the Garnaut Review) and the United Nations Environment Programme's (UNEP) Climate Change Science Compendium (2009). This latter contains:

> …a review of some 400 major scientific contributions to our understanding of Earth Systems and climate that have been released through peer-reviewed literature or from research institutions over the last 3 years … since the IPCC Fourth Assessment Report [15].

It was also in October (2007) that the Nobel Committee awarded the Nobel Peace Prize to, jointly, the Intergovernmental Panel on Climate Change (IPCC) and Al Gore. The IPCC Assessment Reports are arguably the best-known body of scientific work. IPCC's Fourth Assessment Report was published in 2007 (the first was in 1990 and the fifth is expected in 2014). When awarding the Peace Prize in October 2007 the Nobel Committee said that "the IPCC has created an ever-broader informed consensus about the connection between human activities and global warming" [10].

Although they contain region-specific elements, the IPCC reports are global in context. Others are more specific, such as the Garnaut Review (which focused on Australia) and the Stern Review, commissioned by the United Kingdom's Treasury and which reported on both the potential impacts of global warming and the economics of investments in mitigation and adaptation strategies.

One would think that this abundance of evidence is conclusive, but it has met with counterargument. For example, U.S. Senator James Inhofe has famously said:

> Much of the debate over global warming is predicated on fear, rather than science … I have offered compelling evidence that catastrophic global warming is a hoax. That conclusion is supported by the painstaking work of the nation's top scientists [4].

Since its first publication in 2008 there have been three updates to the U.S. Senate's Minority Report citing scientists expressing dissent over manmade global warming claims [4]. A quick search of shelves in a bookstore yields such titles as *Air Con*, *Red Hot Lies*, and *The Climate Caper*, each asserting that scientists are overstating the impact of human behavior on global warming.

Therefore, not only is there a wealth of risk assessment available, there is contention over it.

15.2 Discussion

In 2005 the International Risk Governance Council (IRGC) published its first white paper, "Risk Governance—Towards an Integrative Approach" [7]. IRGC defines as ambiguous those risks for which the scientific evidence is contested or subject to differing interpretations.

So, let us temporarily put to one side the scientific risk assessments and concentrate more on visual indications. Evidence of the impacts of changes to the Earth's climate—whether or not the result of anthropomorphic forcing—is everywhere. One example concerns glacial retreat: as recently as October 2010 the glaciologist Sylvain Coutterand of France's *Centre National de la Recherche Scientifique* was quoted [3] as saying that the Mer de Glace, above Chamonix, has lost 500 m of its length since 1988, when it measured 11 km. On UNEP's website one can see graphic images showing the retreat of the Morteratsch Glacier between 1985 and 2007.[1] As a result, Alpine and other mountain systems are changing, *regardless of how people may differently interpret the scientific data*.

There has also been a measurable increase in sea level. During the period 1961–2003, global average sea level rose approximately 1.8 mm/year and, during the last decade of that period, the rise accelerated to approximately 3.1 ± 0.7 mm/year [5]. The result is that, for example, Venice floods more regularly. Again, the environment in which we live can be seen to be changing, unambiguously.

Despite the recent concerns surrounding certain of the detailed assertions it contains, the work of the IPCC remains the benchmark for scientific input to climate-related policymaking. In its contribution to IPCC's Fourth Assessment Report, Working Group II offers a number of estimates of the likely impacts of global warming in this century. As mentioned above, IPCC's remit and reports are global in context but the Fourth Assessment Report does include region-specific estimates. Those for Europe include [6]:

- [For] nearly all European regions… Negative impacts will include increased risk of inland flash floods, and more frequent coastal flooding and increased erosion (due to storminess and sea-level rise) [level of confidence of at least 9 out of 10].
- In Southern Europe, climate change is projected to worsen conditions (high temperatures and drought) in a region already vulnerable to climate variability, and to reduce water availability, hydropower potential, summer tourism and, in general, crop productivity [level of confidence of about 8 out of 10].
- In Central and Eastern Europe, summer precipitation is projected to decrease, causing higher water stress. Health risks due to heat waves are projected to increase [level of confidence of about 8 out of 10].
- In Northern Europe …as climate change continues, its negative impacts (including more frequent winter floods, endangered ecosystems and increasing ground instability) are likely to outweigh its benefits [level of confidence of about 8 out of 10].

Policymakers struggling to implement austerity budgets and to balance near-term priorities against the longer-term implications of climate change may find difficulty in acting (and committing resources) to mitigate these likely, but imprecisely defined, future changes. In the examples above levels of confidence are high but there are limited projections for timing, nor are there precise locations, adding a further degree of uncertainty to the policymakers' dilemma.

[1] The images can be accessed from the United Nations Environment Programme, DEWA-GRID Europe.

As with the UK's Stern Review and Australia's Garnaut Review, other national governments as well as the European Commission (EC) have sought to bring greater clarity to the impacts of climate change on their territories and populations. The EC-funded PESETA project is one such example and published its final report in 2009 [1]. The report explores four scenarios (mean temperature rises by 2080 of, respectively, 2.5°C, 3.9°C, 4.1°C and 5.4°C) and their impacts on, inter alia, annual mean temperature, annual rainfall, and coastal system flooding.

Figures 15.1 and 15.2 (below) [1] show the annual mean temperature and precipitation changes anticipated across Europe by each of the four scenarios used by the PESETA project. The timescale is relatively long-term (to the 2080s), but the messages for policymakers are relatively clear.

Many of Europe's southernmost countries face relatively marked temperature increases compared to their more northerly counterparts, but annual rainfall is expected to be dramatically lower in the south and higher in the north. There are also distinct differences between countries in the west and those in the east. The PESETA results suggest that the severity of changes increases in line with the mean temperature rise.

In another section the report looks at the potential impacts of global warming on a number of regional welfare factors: tourism, river floods, coastal systems and agriculture. As illustrated below (Fig. 15.3) [1], the regional impacts differ (apart from changes to coastal systems, which are pan-European) and there are particularly adverse impacts on southern and central Europe, as well as the United Kingdom. Although northern European countries may see some positive changes, particularly for agriculture, the suggested overall impact across Europe is negative and includes, for example, heightened pressure on food and water supplies.

The PESETA report examines each of these welfare changes in more detail. Figure 15.4, below, provides more detail on the specific "welfare change" anticipated for coastal systems. There are already a number of coastal plains in Europe prone to flooding during high tides, but the PESETA project foresees heightened levels of coastal flooding for all of England and Sicily as well as parts of Greece, the Netherlands, Germany and Poland. And, this is just Europe!

What can a policymaker do when confronted with a possible future as depicted in Fig. 15.4 [1]? The timescale is such that none of those now in office will be active decision makers when 2085 arrives; possibly, none will be alive. In these days of professional politics and confronted by the inexorable cycle of regular elections and even more frequent opinion polls, the pragmatic approach for policymakers is to deal with more immediate issues. In Europe the issue of coastal flooding and its impacts is made more complex by the fact that planning permits are delegated to local authorities, and are not in the remit of national governments. Thus, a decision about how to change—for example—residential planning authorizations is out of the hands of those who represent their countries at such important meetings as United Nations Framework Convention on Climate Change (UNFCCC) conferences of the parties (COPs).

In my opinion, one drawback of the PESETA Report—and many others—is that their detail is offset by extremely long timescales. Given all the scientific data available

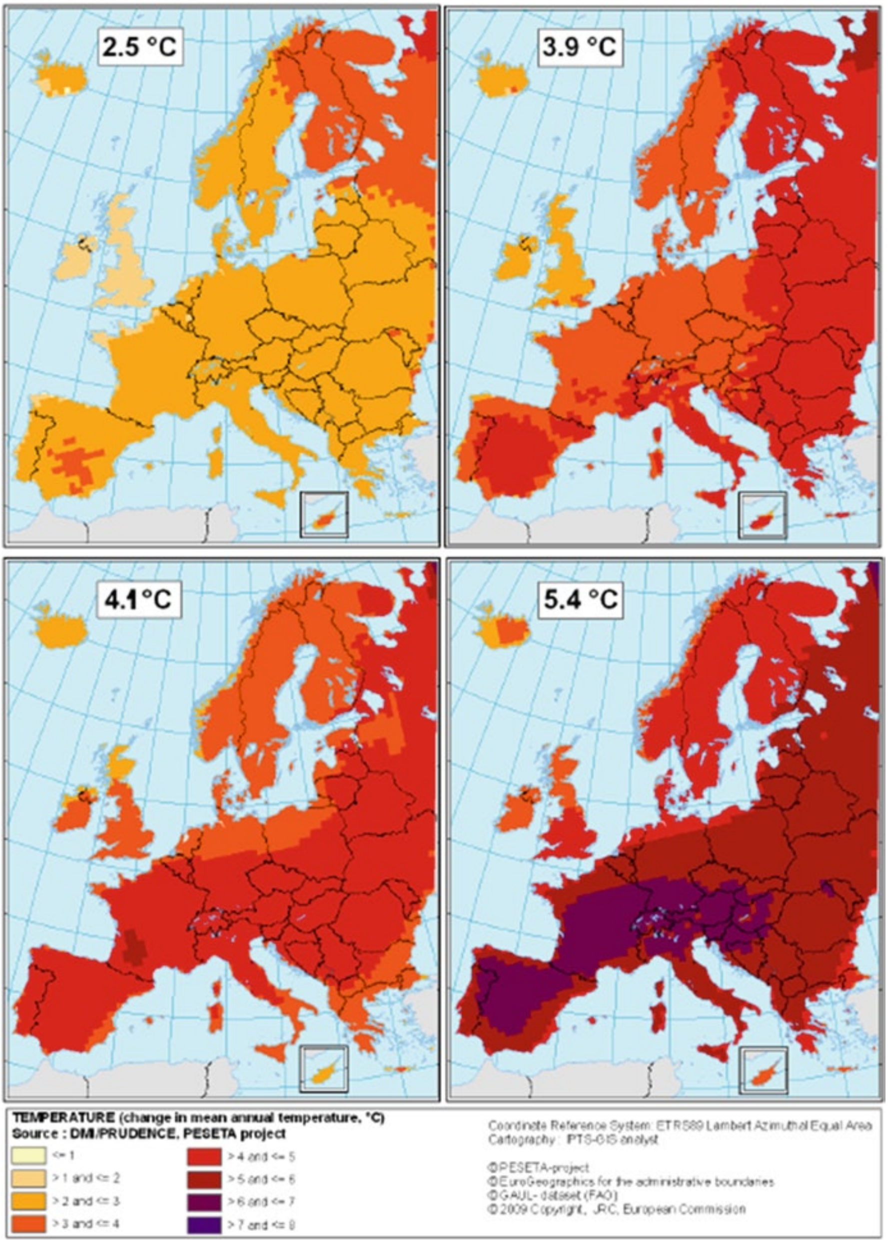

Fig. 15.1 Projected 2080s changes in annual mean temperature—Europe

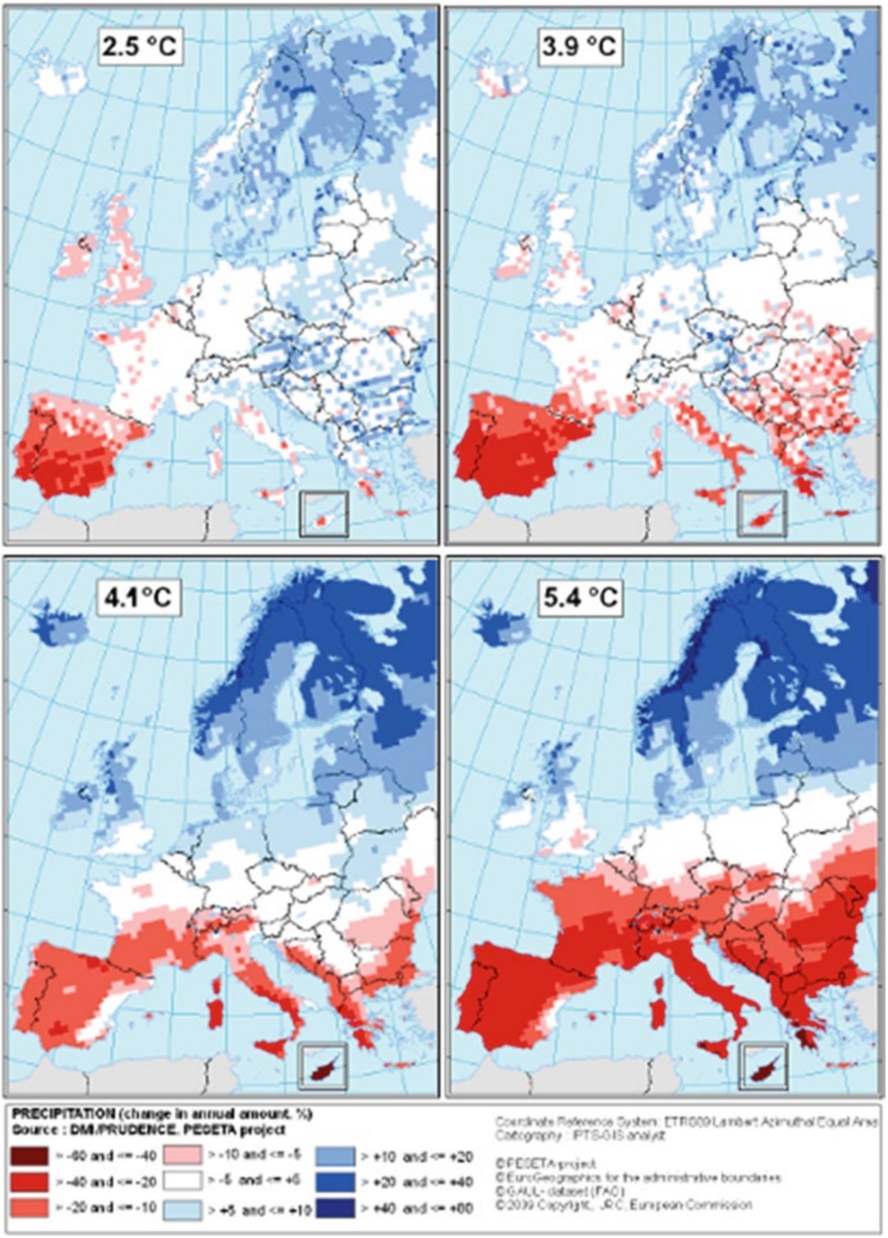

Fig. 15.2 Projected 2080s changes in annual precipitation—Europe

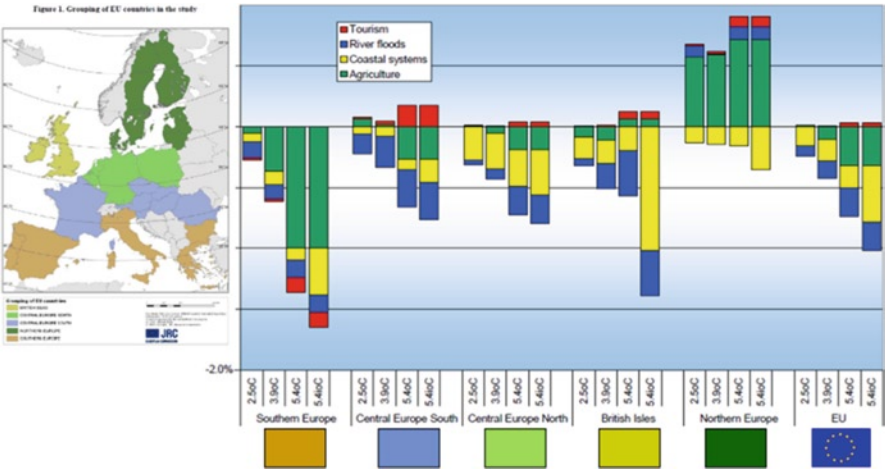

Fig. 15.3 Sectoral decomposition of regional welfare changes (by 2085)

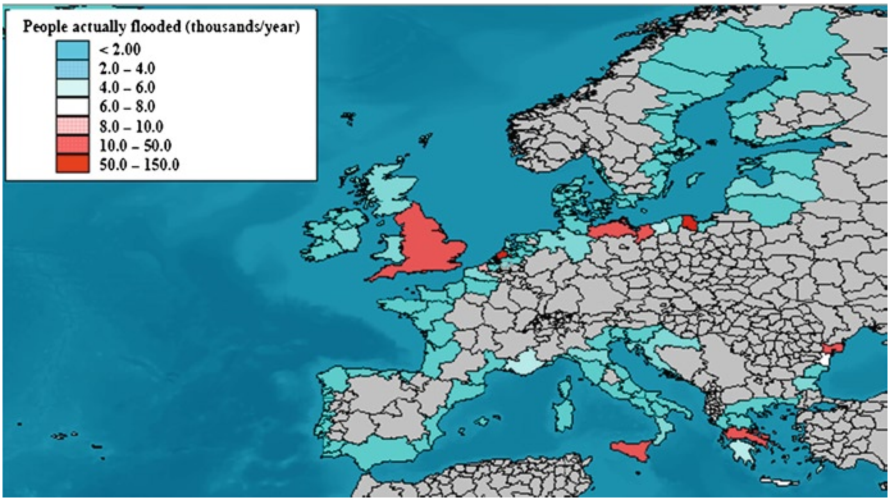

Fig. 15.4 European coastal systems—people actually flooded (1000s/year) across Europe for the PESETA B2 scenario, 2085 (ECHAM4: 4.1°C), without adaptation

(including the Garnault Review and the PESETA Report) by the time of the 15th Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) in Copenhagen, the conference failed to reach a conclusion on how best to reduce the emissions of CO_2 that are so influential on climate change. To this observer, the overwhelming political focus on current economic fragility and the need for stringent national budgets outweighed the known need to curb greenhouse gas emissions.

One irony of the 2009 Copenhagen conference was that it saw protests [14, 17], both in the city of Copenhagen and, perhaps more notoriously, by Greenpeace during the reception for an official dinner for heads of state. These demonstrate that climate change has become a motive for social mobilization in the West in much the same way as were, in the recent past, globalization and, further back in time, nuclear weapons. Alongside the need for policymakers to be informed of knowledge derived from scientific risk assessments, there is also a need to properly understand how people at large view the issue. Without such knowledge, no publicly acceptable decisions can be made, particularly if—as is undoubtedly the case—such decisions require changes to how people behave and, above all, consume.

Within the risk governance framework presented in its White Paper No 1, IRGC recommends that risk managers should combine a scientific risk assessment with a *concern assessment*, taking steps to:

> …understand concerns of the various stakeholders and public groups, information about both risk perceptions and the further implications of the direct consequences of a risk—including its social mobilization potential (i.e. how likely is it that the activity will give rise to social opposition or protest?) … identify and analyze the issues that individuals or society as a whole link with a certain risk.

This combination of risk assessment and concern assessment may be difficult to realize. Many countries (e.g., the UK, China, Switzerland, and the U.S., among others) have national climate impact programs and have published, or will publish, national climate impact assessments. For many, there will be the need to go to a more local level, and this is already happening in, e.g., the U.S. and Canada, but often not through research commissioned directly by the national government [9, 11]. At the same time, there are studies of how people view climate change, its impacts, and their role in their mitigation, but these are normally undertaken as university research, not as a part of a holistic appraisal of what knowledge exists to support the mitigation of or adaptation to the impacts of climate change.

As will now be clear, the civil protection and security implications for one government will not be the same as those for others. Equally, all countries may face some form of civil disturbance caused by sections of the public protesting against either political inaction or, foreseeably, against measures intended to mitigate or adapt to the effects of global warming. Imagine, for example, public reaction to a potential EU decision either to approve the use of GM crops as part of a climate-adaptation policy or to accept large numbers of migrants permanently displaced by climate change.

The Earth's climate system is notoriously difficult to model and inherently "complex" [8]. This complexity is compounded by "uncertainty" (a lack of clarity or quality of the scientific or technical data) and "ambiguity" (divergent or contested perspectives on the justification, severity or wider meanings associated with a given threat). Science cannot provide decision makers with a straightforward, uncontroversial risk assessment, meaning there are no simple policy solutions.

Risk is more than a calculation of the consequences and their likelihood of occurrence: perceptions of risk can be equally important, influencing both how people view and prioritize a hazard as well as how a risk is managed. Thus, values impact on the tolerability/acceptability of risk as much as the scientific knowledge about the risk derived from risk assessments. Governments will, as a result, be extremely reluctant to implement policies that threaten the economy and jobs.

With climate change, values may in fact be the dominant factor at the moment. For example, although there is broad agreement that climate change is threatening the secure supply of food, water and energy, certain behaviors appear to give the impression that people accept the generation of waste more than they fear the scarcity of these essential resources. Here, for me, lies the real security issue posed by climate change.

We all know there is a pending scarcity of food, that drinking water is increasingly insecure, and that, globally, we generate too much waste. Each represents a future challenge to national and global security. What are we— supposedly represented by the protesters at Copenhagen in December 2009—doing for ourselves?

First, food security. It has been said that: "Climate change is a ticking time bomb for global food security" [2]. Additionally:

> DeCarbonnel's conclusion is that … if the public realized the true extent of the crisis and/or prices rose dramatically, economies could collapse and governments could fall [19].

Despite this, according to Waste & Resources Action Programme (WRAP[2]), 8.3 million tons of food are thrown away by UK households every year—one third of the food that is bought.

Next, drinking water. A water exploitation index (WEI) of 20% is a critical value that signals the beginnings of a water shortfall. Countries with a WEI of more than 40% suffer from extreme water shortages and no longer use their available reserves in a sustainable way. Seven European countries—Germany, England and Wales, Italy, Malta, Spain, Bulgaria, and Cyprus—have a WEI of more than 20% [18]. Our consumer-driven reaction?

> The Pacific Institute estimates that in 2006 … It took 3 l of water to produce 1 l of bottled water [12].

Finally, the real conundrum: How to secure energy supplies and mitigate climate change?

> Demand recently has soared because natural gas is the least pollutive of all fossil fuels. But exploration for new gas fields has declined sharply, partly because investors do not consider the rate of return worth the high risk [13].

Our response?

> Annually, over 100 billion cubic meters of gas are flared or vented worldwide—enough to meet the natural gas needs of France and Germany for a year [16].

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[2] WRAP is a not-for-profit private company backed by government funding from England, Scotland, Wales, and Northern Ireland

If climate change and the threats of scarce staples and the reactions of populations to those scarcities are to be taken seriously, such waste cannot continue.

One can summarize the options for risk management as being to prevent the event occurring, mitigate the event and its impacts, and/or adapt to it and its consequences. The climate is changing, as is our environment—demonstrably. Mitigating climate change (e.g., reducing CO_2 emissions) is proving extremely difficult to agree on internationally; the UNFCCC process requires decisions from those who will not be in office when the effects of their decisions bear fruit and, to really have an effect, this will not be possible in an era when balanced national budgets are the political "must have." For me, the more probable future is one in which the man in the street must make sacrifices which, on present evidence, run counter to how consumers are spending their money.

Adaptation is essential, including the use of technologies (although the public's reaction to carbon capture and sequestration and solar radiation management remain unknown). It will also be difficult to prevent scarcities of staples such as food, energy and water, but most of these scarcities will not be experienced equally by all countries, nor equally by all of a nation's population. Some mitigation is possible, through building buffer stocks, but—again—adaptation is necessary. And it is for the consumer to adapt, not the career politician to force change through as policy.

Even if the UNFCCC process can be made to work, our climate will still change. Yes, we can do more to adapt (such as deploy technologies to desalinate sea water to increase the world's supply of drinking water) but, in today's political and economic climate, we need to accept: first, that climate change is already causing our environment to change; secondly, that we as people are failing to adapt our consumer habits to play our part in dealing with the consequences of that change; thirdly, that professional politicians are not in a position to take the severe decisions needed for a top-down approach (and that, if taken, such decisions may not be acceptable to their electorates); and, finally, that each of the three preceding points means that national security resources will be increasingly challenged by climate change and people's reactions both to it and to measures intended to mitigate or adapt to its impacts.

With prevention of climate change not being a feasible option, civil defense and emergency response capabilities will need to have the capacity to deal with a greater number of more diverse events than is the case today.

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Chapter 16
A Critical Review of the Linkage Between International Security and Climate Change

J.L. Samaan

Abstract Increasingly, defense specialists have been considering the international security implications of climate change; however, this immense literature is mainly speculative: it focuses less on the lessons of previous periods of international management of climate change than on the immediate fears that fuel the contemporary debate. We argue here not only that this *securitization* of climate change has weak empirical basis, but it can also mislead policymakers.

16.1 Introduction

In the last few years, it has become almost impossible to track all the publications dedicated to the security implications of climate change. More and more, defense intellectuals and military planners have been taking into serious consideration, if not at the operational level at least at the intellectual one, the issue of the evolutions in the natural environment and their consequences for the international security system [11, 13, 20].

Nevertheless, this immense literature is mainly speculative; it focuses less on the lessons of previous periods of international management of climate change than on the immediate fears that fuel the contemporary debate: water wars, climate refugees, and so forth. The linkage between environmental changes and strategic trends appears so obvious in the logic of this literature that authors do not even try to assess

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the relevance of their belief in light of historical data. In other words, the strategic debate on climate change tends to articulate itself around the *a priori* pessimistic idea that it will generate major conflicts [12]. We argue here not only that this *securitization* of climate change has weak empirical basis, but it can mislead policymakers.[1]

16.2 The Current State of Climate Change

Before discussing the terms of the strategic debate on climate change, it is important to review current environmental trends. As of today, the scientific uncertainties of climate change are less about the likelihood of the change *per se* than about its projected pace. In other words, the question mark is not *if* but *when*.

In its 2007 Assessment report, the United Nations Intergovernmental Panel on Climate Change (IPCC) underlined that the period from 1995 to 2006 represented the warmest years since the creation in 1850 of techniques to record global surface temperature. From 1870 to 2010, surface temperature of the Earth rose 0.8°C [17]. If this phenomenon is global, it is even worse in higher northern latitudes. In the second half of the twentieth century, in the Northern Hemisphere, temperatures were

> …very likely higher than during any other 50-year period in the last 500 years and likely the highest in at least the past 1,300 years [9].

According to the historical records available since the 1950s, ocean temperatures have also been rising, especially since the early 1980s [17]. In the Arctic region, this led to a substantial reduction of ocean ice, which decreased from 8.5 million km^2 (in 1950–1975) to 5.5 million km^2 (2010) (Fig. 16.1).

This evolution is mainly due to the rise in greenhouse gas emissions (particularly carbon dioxide; i.e., CO_2). Between 1970 and 2004, CO_2 annual emissions grew by about 80% and represented 77% of total greenhouse gas emissions in 2004 [9]. Unquestionably, this trend is caused by human activity related to energy supply, transport, and industry.

Geographically, the most affected regions are Asia, Africa, and the Middle East. In Asia, many of the glaciers that feed Asia's great rivers (the Yellow, Yangtze, Mekong, Salween, Indus, Ganges, and Brahmaputra) are already melting "at an alarming rate" [14]. Under current trends, coastal areas in South, East, and Southeast Asia will confront increasing risks of flooding. Bangladesh will be at risk of devastating floods and monsoons, melting glaciers, and tropical cyclones originating in the Bay of Bengal.

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[1] The argument of securitization theory is that security is a speech act fundamentally based on the perceptions of its originators. Ole Weaver explains that "it is by labelling something a security issue that it becomes one" [21].

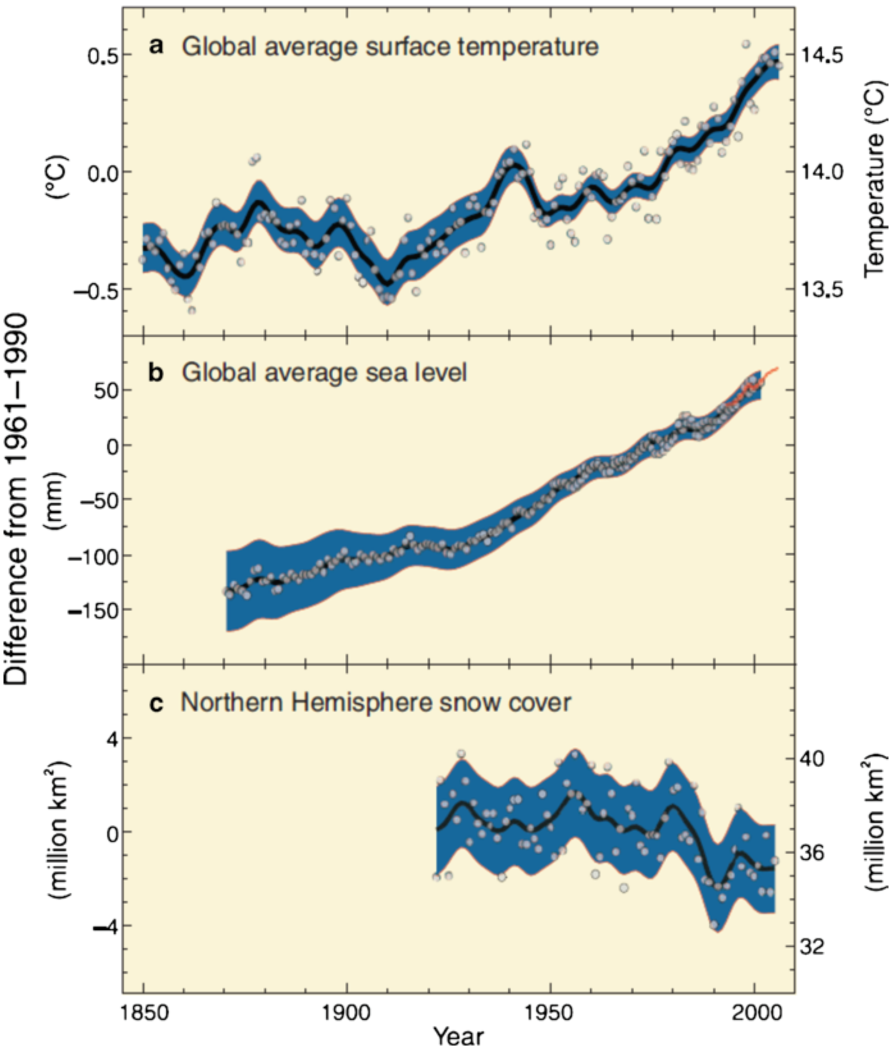

Fig. 16.1 Changes in temperature, sea level, and northern hemisphere snow cover [10]

In 2006, for the first time, an inhabited island, Lohachara—in India's part of the Sundarbans, where the Ganges and the Brahmaputra rivers empty into the Bay of Bengal—disappeared beneath rising seas. Moreover, in the coming decades, the existence of other small islands from the Indian Ocean to the Pacific Ocean (Diego Garcia, Maldives, Vanuatu) is going to be jeopardized by rising sea level.

In Africa, by 2020, between 75 and 250 million of people are projected to be exposed to water stress due to worsening droughts [9]. On average, the continent is 0.5°C warmer than it was 100 years ago but some areas have been subjected to worse increases: parts of Kenya have become 3.5°C hotter than 20 years ago [3].

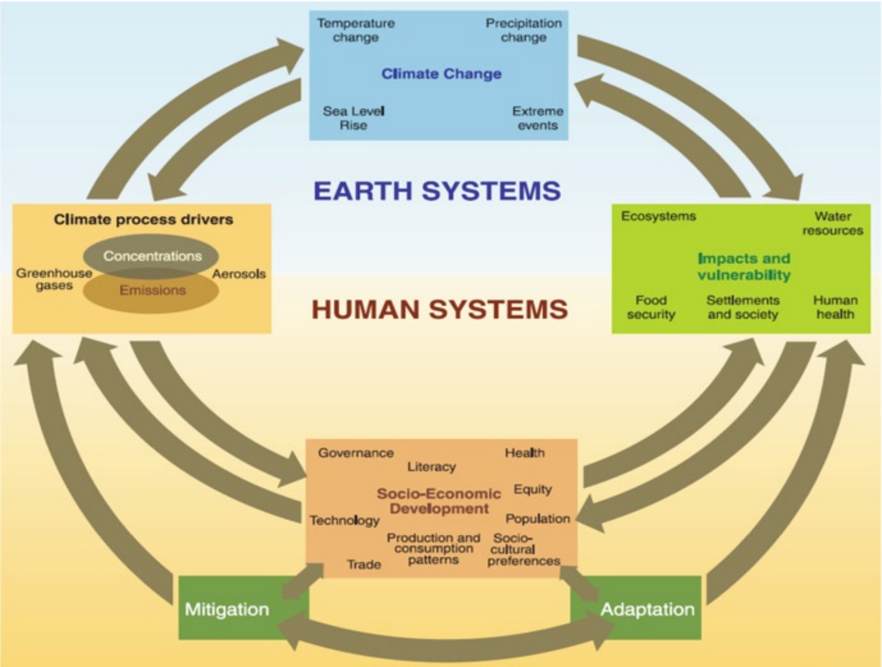

Fig. 16.2 Schematic framework of anthropogenic climate change drivers, impacts and responses [10]

Trends in the Middle East are also extremely worrying. Forecasters expect the Mediterranean to rise 30 cm to 1 m in this century. Such a rise would affect 42,000 km^2 (four times the size of Lebanon) of land; Egypt, Bahrain, and Qatar being especially vulnerable [18]. As a result, grasslands, livestock, and water resources in the Middle East are likely to be exposed to climate change.

All in all, there are several identified impacts of climate change, such as the effects on ecosystems (e.g., biodiversity), health (malnutrition, death, and disease due to extreme weather events), and population migration from coastal areas (expected to endure increasing risks with the rise of sea level). But as the diagram from the IPCC below shows, this chain of causes and consequences goes beyond the exclusive scope of the hard science of climatic change and requires a comprehensive analysis of the interaction between evolving earth systems and human systems. This is when the strategic debate on climate change appears (Fig. 16.2).

For years now, the question of identifying the likely security implications of climate change has produced an intense international debate. In a much-discussed report issued in 2007, the U.S. think tank, Center for Naval Analyses, observed:

> …in the national and international security environment, climate change threatens to add new hostile and stressing factors. Climate change acts as a threat multiplier for instability in some of the most volatile regions of the world [6].

Noticeably, the literature on climate change emphasizes the risks for international security implied by the environmental phenomena. Two types of causalities are worth exploring here: first, the potential for resource wars, and more particularly, conflicts over water; second, the relevance of the issue of climate refugees.

First, according to some pundits, one of the obvious consequences of climate change, the increasing scarcity of vital supplies (water, food) in areas like South Asia and the Middle East, will trigger conflicts between Turkey and Syria, Syria and Israel, Egypt and Sudan, India and Pakistan and so forth. At first, this scenario sounds coherent, especially in light of the structural interdependency of states: today, 214 major river systems are shared by two or more countries.

Former United Nations Secretary General Kofi Annan warned in March 2001 that "fierce competition for fresh water may well become a source of conflict and wars in the future" and the U.S. intelligence community has been discussing the likelihood of coming interstate conflicts for a decade [1]. This is why Professor Thomas Naff characterizes water as a:

> …highly symbolic, contagious, aggregated, intense, salient, complicated, zero-sum, power- and prestige-packed issue, highly prone to conflict and extremely difficult to resolve [15].

Moreover, in the Middle East, Turkey, the only country that does not depend on water supplies that originate outside of its borders, is implementing a gigantic Southeastern Anatolian Project comprising dams on the Euphrates river that would severely deprive Syria and Iraq of water flows fundamental to their economies. As Turkish projects exacerbate Syria's needs, tensions could then grow between Syria and Israel regarding the issue of the Golan Heights, a territory gained by Israel after the 1967 war that now controls 33% of Israel's water resources. In that perspective, one could imagine a scenario around 2020–2025 where a Syrian regime, suffering from bad economic prospects and booming demography, gets more and more assertive abroad and eventually wages a war over the water supplies of the Golan Heights.

Indeed, all around the world there are many instances in recent years tending to support the notion that water disputes are brewing and could in the coming years engender conflicts. But the major flaw in this current discourse on water wars—or, more generally, resource wars—is that historical data does not support the automatic linkage between supply disputes and warfare. A detailed survey of all these situations over the last 50 years (accounting for 1831 international water-related events) revealed that "two thirds of these encounters were of a cooperative nature" [16]. Moreover, in the history of international relations, the only explicit case of a war over water occurred more than 5,000 years ago between two cities, Lagash and Umma, in Mesopotamia [16]. As a matter of fact, when looking at the roots of interstate conflicts, political scientists usually evaluate environmental scarcity as of secondary importance compared to geographical proximity or the nature of political regimes [8]. Not only does the scenario of water wars lack historical data but it implicitly assumes a natural inclination in governments in the Middle East and South Asia to wage wars for these reasons. As Jon Barnett cautiously underlined:

> …the environment-conflict literature is almost entirely premised on the ethnocentric assumption that people in the South will resort to violence in times of resource scarcity. Rarely, if ever, is the same argument applied to people in the industrialized North [2].

Furthermore, because of this bias in the contemporary strategic literature, there are several understudied cases of regional cooperation over water scarcity: for instance, the case of the Okavango River. In Southern Africa, the Okavango River, which is shared by Angola, Botswana, and Namibia, has been at the core of tensions between these states. To mitigate the risks of a regional conflict, the three countries signed an agreement in 1994 to form the Permanent Okavango River Basin Water Commission. Since then, this intergovernmental organization has been effective at managing the river.

Even in places seen as the most inclined to conflicts over resources such as South Asia, there are concrete cases of cooperation: the Indus Water Treaty negotiated between India and Pakistan in 1960 is an example of a successful resolution of a major dispute over international waters [14].

Resource wars are only one of many fads that can be found in defense publications. The other very questionable idea is the one of climate refugees. As a matter of fact, the expression, "climate refugees," has become a standard term in the literature dedicated to environmental security. True, the United Nations has estimated that there could be "millions" of environmental migrants by 2020 [7].

Simply said, the expression is based on the following syllogism: (1) climate change will displace population; (2) migration generates international instability; (3) migration caused by climate change will create conflicts.

This syllogism is at the core of several strategic assessments of climate change. For instance, looking at the prospects in South Asia, John Podesta and Peter Ogden assume:

> … the combination of deteriorating socioeconomic conditions, radical Islamic political groups, and dire environmental insecurity brought on by climate change could prove a volatile mix with severe regional and potentially global consequences [16].

Obviously problematic, this general idea includes climate change as part of a deadly combination with Islamism and failing states without clearly characterizing the interaction between these factors. But Podesta and Ogden's appraisal is even more debatable when it comes to the indirect consequences for Europe:

> Because most African and South Asian migration will be internal or regional, the expected decline in food production and fresh drinking water combined with the increased conflict sparked by resource scarcity will force more Africans and South Asians to migrate further abroad. The result is a likely surge in the number of Muslim immigrants to the European Union, which could exacerbate existing tensions and increase the likelihood of radicalization among members of Europe's growing and often poorly assimilated Islamic communities [16].

In other words, in the authors' perception, the issue of climate change should be addressed because of the collateral effects on the tense relation between European countries and their immigrants. This belief relies upon two assumptions: first, the unprecedented nature of the climate refugees phenomenon; and second, the cause-consequence chain (as mentioned by the syllogism above) between migration and instability.

But both assumptions are debatable: natural disasters (earthquakes, hurricanes…) have always led to massive population displacements so the phenomenon is not different with climate change. But moreover, there is rare evidence from history that massive movements of environmental refugees led to violent conflicts. Even in the extreme case of Bengalis fleeing natural disasters and land degradation in Bangladesh to migrate to northeast India (about 17 million since the 1950s); this did create instability but that was disorganized, small-scale violence, not an armed conflict [5, 19].

The idea of climate refugees is then first and foremost about Western fears of gigantic and uncontrolled migrations from poor countries to Europe. In this logic, population growth is the implicit issue. In 1984, Robert McNamara, former U.S. Secretary of Defense and former director of the World Bank, explicitly said:

> …short of thermonuclear war itself, population growth is the gravest issue the world faces over the decades immediately ahead [2].

This analogy between nuclear war and demography tells us a lot about the assumptions driving such views of the implications of climate change for population displacement.

Both cases, resource wars and climate refugees, illustrate the increasing tendency to put climate change into the classic theoretical framework of the realist school of international relations which focuses mainly, if not exclusively, on the causes of conflict. Some proponents of this approach acknowledge that this securitization of climate change may be alarmist rhetoric but assert that it is necessary to increase public awareness about the issue [12]. But to be cautious, one should not misunderstand the most important thing: refuting the securitization of climate change does not mean refuting climate change. As expressed before, the scientific observations on the warming of the earth are "unequivocal" [9]. Nevertheless, securitizing climate change does not strengthen the policy debate: it risks distorting approaches to address the phenomenon.

16.3 Human Security and Climate Change: Articulating the Right Policy Discourse

The securitization of climate change is a conflict-driven debate that leads to a biased geopolitics. In this vision, climate change is to become a new field of power plays and state-to-state rivalries. As a so-called "threat multiplier" [6], it is a new variable for existing conflicts in the Middle East and South Asia. In this context, Yoweri Museveni, President of Uganda, in 2007, called greenhouse gas emissions an "act of aggression" by the developed world against the developing world; and Margaret Beckett, former British Foreign Secretary, explained that "a failing climate means more failing states" [4].

Securitizing climate change does not increase public awareness; it simply creates an attractive policy context to apprehend the problem and not solve it. The securitization of climate change is counterproductive speech because it leads to inappropriate strategic or military options: predictions of resource wars imply that climate change is a mission for the armed forces.

Au contraire, the history of governance of natural resources proves that good practices have originated from a bottom-up, human-centered approach and not a top-down, state-centric one. Consequently, if one had to depict the security implications of climate change, the right discourse should focus on human security and the response should target populations. This shift from states to people has several policy values:

- First, the desecuritization lowers the level of political sensitivity surrounding the issue. In regions enduring protracted territorial disputes (Middle East, South Asia), it disconnects the core irritants (political symbols, military postures) from climatic issues affecting population from all countries.
- Second, it eases the involvement of international organizations (United Nations, European Union, and other regional actors) that would otherwise be accused of illegitimate interference. At the operational level, international organizations can help build a robust governance framework.
- Third, this process can then depoliticize the potential disputes over resources and provide a path for a technical, bottom-up approach of responses to climate change.

Of course, one could object that the policy goals of this approach are too modest, focused on the regional and not the global level; and more particularly that this approach does not directly address the other big issue of climate change: the reduction of CO_2 emissions. In fact, while both processes are distinct, they should complement each other. Diplomatic efforts to reduce greenhouse gas emissions aim to mitigate the effects of climate change on the natural environment while a policy of human security can create the cooperative conditions that prevent misperceptions and subsequent miscalculations at the international security level.

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Chapter 17
The U.S. Navy's Approach to Climate Change and Sea Level Rise

T.C. Gallaudet and C.C. St. John

Abstract Climate change and its associated effects such as sea level rise, ice sheet melting, and changing storm and precipitation patterns are being observed on global and regional scales around the world and will influence the way the U.S. Navy operates in the twenty-first century. In response to the overwhelming scientific evidence that climate change is occurring, and recognizing that climate change is a national security threat with strategic implications for the Navy, the Navy's Task Force Climate Change and Task Force Energy are executing Navy *Arctic* and *Climate Roadmaps* and a *Navy Energy Strategy*. The *Climate Change Roadmap* outlines the Navy approach to assessing, predicting, and adapting to climate change to ensure that the Navy is mission ready in order to meet the challenges of the future.

17.1 Background

Melting Arctic sea ice, the stability of developing and resource-poor nations, changing fish stocks in Asia, and more intense hurricanes in the Atlantic Ocean…what do all of these scenarios have in common? All are caused or affected by changing climate, and they represent only a fraction of climate change concerns for the Navy and the nation. There is broad scientific consensus that climate change is occurring on a variety of scales around the world with economic, human health, societal, and national security implications. This paper examines the national security implications of climate change and their impacts on U.S. Navy missions, force structure, and infrastructure.

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17.2 Observations

To understand how climate change will affect the U.S. Navy, one must first comprehend the science. Despite criticism of reports published by the Intergovernmental Panel on Climate Change (IPCC), extensive observations of the Earth's atmosphere, oceans, biosphere, and cryosphere confirm that the planet's climate is changing.

17.2.1 Temperature and Greenhouse Gases

Global average temperature since 1990 has risen about 1.5°F [27]. In a recent paper submitted to Reviews of Geophysics, Dr. James Hansen observes that global warming on decadal time scales is continuing, concluding that there has been no reduction in the global warming trend of 0.15–0.20°C/decade that began in the late 1970s [7]. Figure 17.1 illustrates this point, displaying the Global Temperature Anomaly with correlation to the Nino (El Nino and La Nina index) and large volcanic eruption cooling effects that last approximately 2 years. While the graph demonstrates these short-term fluctuations in temperature, the observed trend of steadily increasing global temperatures since the 1970s is clear.

The link between increasing global average temperature and greenhouse gas emissions should not be as contentious as it has become. The greenhouse effect is well-understood physical phenomena governed by the radiative transfer equation and by which greenhouse gases such as methane and carbon dioxide absorb incoming solar radiation and re-radiate it to the atmosphere, thereby increasing global temperature [5]. Without the greenhouse effect, the Earth's average global surface temperature would be −32°F, which thankfully is not the case. However, increasing concentrations of greenhouse gases in the atmosphere beginning in the Industrial Revolution have led to corresponding increases in global temperature. The 2007 IPCC Report of the Fourth Working Group (AR4) states with very high confidence that the global average net effect of human activities since the 1750s has been one of warming [10].

The world's oceans and land absorb significant amounts of this heat and energy. In fact, about 45% of the carbon dioxide emitted by human activities in the last 50 years is now stored in the oceans and vegetation [27]. Other effects of rising global temperatures that are observed today include increasing frequency of heat waves, changing precipitation patterns, and shifting plant and animal habitat.

17.2.2 Sea Ice and Ice Sheets

Because the Arctic is warming twice as fast as the rest of the globe, the region is experiencing declining sea ice extent and volume, increasing glacial and ice sheet melt, and shrinking snow areas [11]. Sea ice extent in the Arctic has decreased steadily since the 1950s and in September 2007 reached a record low 39% below the

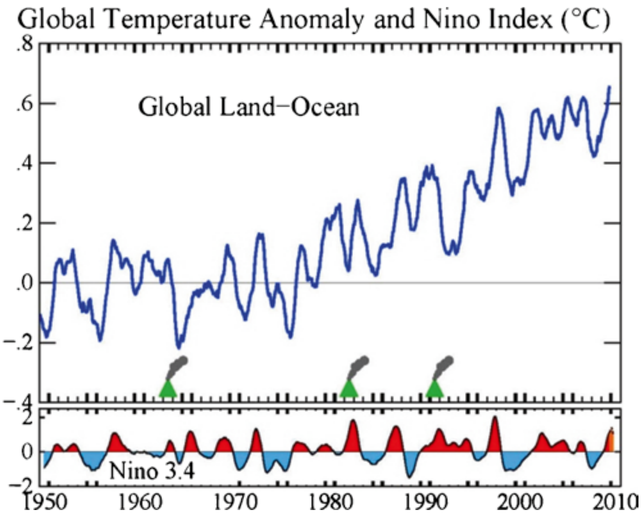

Fig. 17.1 *Blue curve*: 12-month running-mean global temperature. Nino index (*red* = El Nino, *blue* = La Nina). Large volcanoes are in *green* and have a cooling effect for ~2 years [7]

1979–2000 mean. The minimum sea ice extent for September 2010 was the third lowest recorded in the 1979–2010 satellite record, above only 2007 (the record low) (see Fig. 17.2) [19]. Monthly average Arctic Ice Volume for September 2010 was 4,000 km^3, the lowest over the 1979–2010 period, 78% below the 1979 maximum and 70% below its mean for the 1979–2009 period [31]. Reduction in ice volume means that thicker, multiyear sea ice is being replaced by first-year or "seasonal" ice in the Arctic, which is thin and much more susceptible to melting or being influenced by wave and wind action.

Also exhibiting significant decline is the mass of the Greenland Ice Sheet (GRIS), and this trend has recently been observed to be accelerating (see Fig. 17.3)[1]. Observations indicate a large increase in summer 2007 ice melt at 60% more than the previous high in 1998 [13]. Antarctica's ice sheet has exhibited a similar trend [1].

17.2.3 Sea Level Rise

Ice sheet melting is one of two processes that contribute to global sea level rise. The net GRIS ice loss is contributing as much as 0.7 mm per year to sea level rise due to expanded melting and accelerated ice flow, and the Antarctic ice melt is contributing to sea level rise at a rate nearly equal to this [1]. Rising global ocean temperature also contributes to increased global sea level rise through thermal expansion of warming ocean water. Both ice sheet melting and global ocean warming contributed to historic sea level rise, which has been carefully reconstructed dating back to the last ice age by geologists using the dates and depths of coral reefs [18].

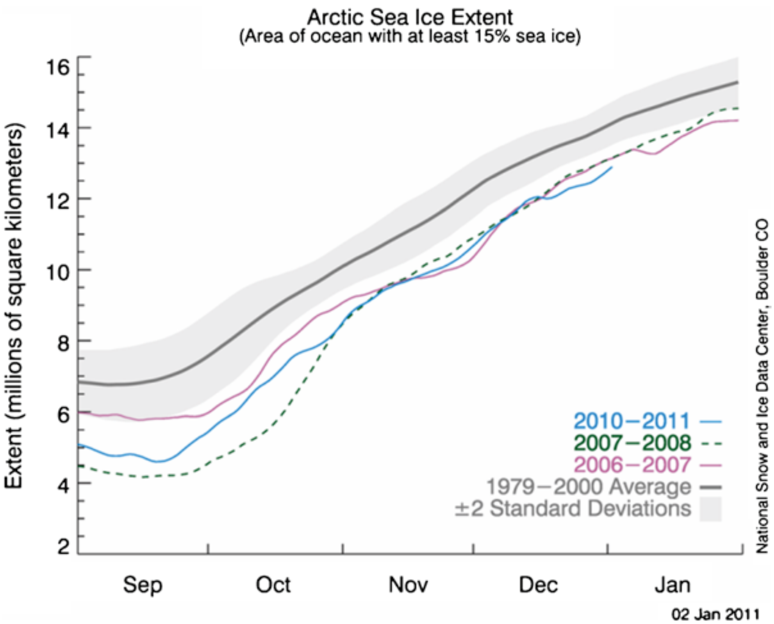

Fig. 17.2 2010–2011 ice extent is currently under the 2006–2007 and 2007–2008 averages [19]

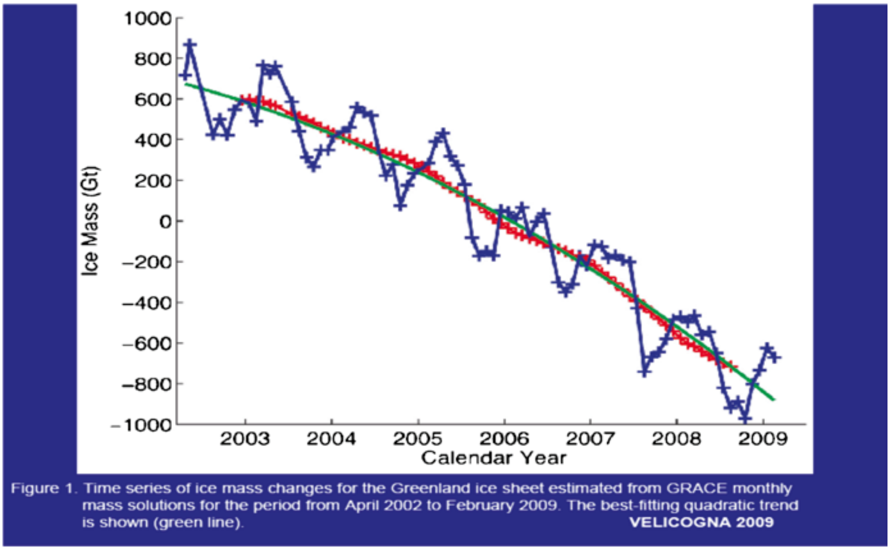

Fig. 17.3 Greenland Ice Sheet mass loss is accelerating [29]

Their data show that changes in sea level were punctuated by sharp, unsteady increases attributable to melting ice; 6,000 years ago global average sea level was roughly equivalent to its present-day level and remained relatively steady from the first century AD to 1800 [18].

For the nineteenth and twentieth centuries, sea level has been recorded using tide gauge measurements which date back approximately 140 years. These observations indicate that sea level has been rising since the mid-nineteenth century at approximately 2 mm a year [14].

More recent and accurate satellite altimeter measurements have been used to record global sea level since 1993, indicating a 3.4 mm/year increase, 80% faster than the best estimate of the IPCC Fourth Assessment Report (AR4) for the same period. This disparity is almost certainly due to the omission of ice sheet contributions in the projections used in the IPCC AR4 [1, 18].

17.2.4 Extreme Events and Variability

While observed trends in global averages are significant, variability and extremes relative to these averages are expected to have mostly adverse impacts on natural and human systems, altering the time available for humans to recover and adapt [10, 27]. The U.S. Global Change Research Program (USGCRP) notes that the cumulative effects of these events is compounded in that they usually occur concurrently and have more severe impacts; for example, heat waves, droughts, air stagnation, and wildfires in California can feed off of one another and cause greater damage than if they occur singularly.

Examples of changes in extreme event patterns are many. The last 10 years have seen fewer cold waves than any other 10-year period in the historical record, extreme precipitation episodes have become more frequent and intense, and droughts are becoming more severe in some regions [27].

On the other hand, the data for tropical cyclones are mixed. No link between climate change and the number of tropical cyclones has been identified [10], and Accumulated Cyclone Energy Index from 1950 to 2009 showed no clear trends in cyclone frequency [26]. However, the EPA does note that intensity has risen noticeably over the past 20 years, and six of the ten most active years occurred since the mid-1990s [26].

Understanding climate variability is even more elusive. Recent data released by the National Oceanic and Atmospheric Administration (NOAA) illustrates that despite a severe and cold winter for much of the U.S. this year, combined land and ocean temperatures for April 2010 were the warmest on record at 58.1°F, which is 1.37°F above the twentieth century average. Snow cover extent was also the fourth-lowest on record (since 1967) and below the 1967–2010 average for the Northern Hemisphere for the seventh consecutive April [16]. This type of vacillation from one extreme to the next will make it very challenging for populations around the world to adapt to a changing climate in a safe and timely manner. Improved understanding of predicted events is integral to the climate change planning and adaptation process.

17.3 Predictions

Climate change scientists use physical models and historic and observed trends to predict future change. While one must recognize that significant uncertainties remain in modeling possible outcomes of global change, these predictions are essential to the Navy and other organizations as they provide a foundation of scientifically based projections for adapting to and planning for likely situations.

17.3.1 Temperature

While scientists observe that global emissions of carbon dioxide and other greenhouse gases are accelerating, it is impossible to predict the exact rise in future temperature due to the uncertainty in predicting future emission scenarios. However, under a business-as-usual global emission scenario, the average-annual temperature increase in the U.S. is likely to reach 4–6°F by 2050 and 7–11°F by 2090 [27]. While the increase of a few degrees over decades may not seem like an immense problem, consider that the climate observations discussed in the sections above have occurred in a world that has warmed on average only about 1.5°F since 1990 [8]. Indeed, the IPCC states that global average temperature is projected to rise by 2–11.5°F by the end of this century based on scenarios that do not assume explicit climate policies to reduce greenhouse gas emissions.

But even if greenhouse gas emissions stabilize, the time lag in climate response will cause warming to continue for many years. The effects of increased warming on other climate processes must be considered when projecting future scenarios.

17.3.2 Sea Ice and Ice Sheets

Warmer global temperatures will continue to have a significant effect on the coldest regions of the world, including sea ice and ice sheets. Holland et al. [9] suggest that the Arctic could experience an ice-free summer in the late 2030 period. Rapid melting of Arctic sea ice likely will trigger permafrost melting and warming on land [1]. The Greenland and West Antarctic Ice Sheets have the potential to trigger massive sea level rise around the world if they experience continued melting. The *Copenhagen Diagnosis* states the if completely melted, the Antarctic ice sheet would raise global sea level by 52.8 m and loss of only the most vulnerable parts of West Antarctica would still raise sea level by 3.3 m; Greenland would add another 6.6 m.

17.3.3 Sea Level Rise

Based on the exclusion of melting ice sheets from the IPCC AR4 Report, recent scientific observations and modeling efforts like those cited above have concluded the that prediction of 18–59 cm of sea level rise by 2100 in the IPCC AR4 Report is too conservative [1]. Based on a number of new studies, the synthesis document of the 2009 Copenhagen Climate Congress [22] concluded, "updated estimates of the future global mean sea level rise are about double the IPCC projections from 2007" [1]. According to Vermeer and Rahmstorf [30], the higher emission scenario under which we are currently tracking yields a global sea level rise by 2100 of about 1.4 m. This figure is countered by other scientists who state that this figure represents a linear relationship between global temperature and sea level rise which is not entirely acceptable because there is the risk of the climate reaching "tipping points" (e.g. Arctic sea ice, ice sheet melt, Amazon deforestation) that could trigger rapid, nonlinear change in sea level rise.

Another component of sea level rise is regional change. Regional sea level change is affected by a number of factors including local atmospheric pressure, alongshore wind stress, integrated water column density and thermocline depth, and short-term effects from processes such as El Nino. The effects of global sea level rise will be exacerbated by regional changes, making it necessary to understand these processes on both global and regional scales.

As with global temperature, sea level will continue to rise for many centuries after global temperature is stabilized. If the United Nations Framework Convention on Climate Change (UNFCCC) negotiations are successful and global greenhouse gas emissions are capped within the next few years, the world will still have to contend with rising sea levels as the oceans and ice sheets fully respond to a warmer climate.

17.3.4 Extreme Events

Despite lack of an observed relationship between climate change and risks of extreme weather events, the IPCC report identifies a higher confidence in the projected increases of drought, heat waves, and floods in many regions around the world. Increased storminess, sea level rise, and associated storm surge will continue to accelerate over the twenty-first century and will have dramatic impacts on low-lying areas where subsidence and erosion problems already exist [4].

The lethal storms and subsequent floods in Nashville in May of 2010 demonstrate the severity and suddenness with which extreme events will occur. In one weekend, Nashville experienced its heaviest 1- and 2-day rains on record, receiving 7.25 in. of rain on Sunday, killing 15 people, closing highways, causing unprecedented flooding of rivers, and damaging homes [2, 12]. These types of events are predicted in the USGCRP's 2009 *U.S. Climate Impact Report*. The report observes:

> …the amount of rain falling in the heaviest downpours has increased approximately 20% on average in the past century, and this trend is very likely to continue, with the largest increases in the wettest places.

The storms in Tennessee illustrate on a small scale the kind of extreme events that can wreak havoc on communities, states, and countries. With increasing frequency, the call for help will be heard from regions around the world. The U.S. Navy must be prepared to operate under shifting conditions as extreme events related to climate change increase.

17.4 Navy Concerns

What implications does a changing climate have for the Navy? The 2010 Department of Defense Quadrennial Defense Review (QDR) identified two broad ways in which climate change will affect DoD. First, climate change "will shape the operating environment, roles, and missions" that DoD undertakes. The projected effects of climate change will have geopolitical impacts around the world that will contribute to poverty, environmental degradation, further weakening of fragile governments, and resource scarcity. In the sense that it will accelerate instability, climate change can be deemed a "threat multiplier" for the Department of Defense [25].

The second consideration for DoD identified in the QDR is the ways in which it will have to adjust to the impacts of climate change on military capabilities and facilities. The Navy in particular locates the majority of its installations along coasts that will be increasingly vulnerable to the impacts of extreme events and sea level rise.

17.4.1 Continental U.S. Installations

In its recent report entitled "Advancing the Science of Climate" (part of its America's Climate Choices project), the National Research Council notes that many U.S. military bases are located in areas likely to be affected by sea level rise and tropical storms, and that future military operations may take place in areas subject to drought or extreme high temperatures [18]. A 2008 report by the National Intelligence Council noted that more than 30 U.S. military installations were already facing elevated levels of risk from rising sea levels. As the QDR states, DoD's operational readiness hinges on continued access to land, air, and sea training and test space. A 2010 Letter Report to the Chief of Naval Operations from the National Academies' Naval Studies Board suggests that the Navy conduct a detailed analysis and action plan to address vulnerabilities of coastal installations identified as being high risk or very high risk, taking into account risk factors such as regional weather history, shifts in storm tracks, changes in ocean circulation, and the impact of groundwater drawdown and recharge on subsidence [20]. This kind of work will help inform larger risks to Navy installations and ensure that the Navy understands and can adapt to changes that will occur on its Continental U.S. (CONUS) installations.

17.4.2 Overseas Installations

Overseas installations are also of extreme importance to the Navy. In addition to the basic climate change concerns discussed for CONUS installations that also need to be addressed overseas, bases such as Guam and Diego Garcia provide a strategic advantage to the Navy in terms of location, ease of access to different regions around the world, and logistics support. The U.S. Navy frequently engages other navies via port visits, and climate change threats to these foreign bases will stymie the Navy's ability to maintain friendly relations and access to the global commons.

17.4.3 Water Resources

As the climate changes, both the quantity and quality of water resources will become increasingly scarce due to the changing precipitation patterns and amounts discussed above. The U.K.'s Met Office states that 1.5 billion people currently live in water-stressed regions and climate change and population growth could increase this to nearly seven billion by the 2050s. Significant population changes like these will place considerable additional stress on water resources, intensifying competition for the precious resource, which in turn can lead to regional water and food shortages, mass migration, and poverty [24].

Alterations in freshwater systems will also present challenges for flood management, drought preparedness, and water supply [18]. In regions such as the southwest and southeast U.S., drought is already a problem and will need to be continually addressed for Navy installations as climate change intensifies. Additionally, shifting water resources are likely to increase humanitarian assistance and disaster relief missions for the Navy.

17.4.4 Humanitarian Assistance and Disaster Relief

One hundred-sixty million people around the world live less than 1 m above sea level and these people are at risk from more intense coastal storms, flooding, and erosion [1]. While the exact estimates of increases in extreme events are uncertain, the National Intelligence Council estimates that demand for food will rise by 50% by 2030 as a result of growing world population, rising affluence, and a shift to Western dietary preferences, resulting in greater stresses on resources already under pressure from climate change effects [15]. Combined, these factors suggest a potential for increasing humanitarian assistance and disaster relief (HA/DR) requirements. However, further study is needed to examine the complex interplay between climate, resources, and regional and national economic, political, and security considerations that influence decisions to perform HA/DR missions.

17.4.5 Wild Card Scenarios

The Navy is concerned with climate change *wild cards*, or those aspects of climate change for which little is known or has been addressed by the climate science community. One such wild card is abrupt climate change set off by *tipping elements*. Tipping elements are defined as earth system components vulnerable to such abrupt change, such as the Indian summer monsoon, Atlantic ocean thermohaline circulation, and the Amazon rainforest. Tipping elements do not follow linear paths of change and thus present a challenge to climate scientists and modelers in observing and predicting future events; the significance of tipping points in the climate system being reached means that the observations and climate phenomena discussed earlier will likely become even more unpredictable, with greater need for military response [13].

A second wild card is ocean acidification. The world's oceans have absorbed approximately 40% of fossil fuel emissions, currently totaling about one third of the total emissions from the past 200 years [3]. The uptake of CO_2 into the world's oceans is the basis of unprecedented modifications to ocean chemistry, which in turn causes a domino effect of changes to a myriad of ocean organisms, including fisheries that millions of people around the world depend upon as a food source [17]. Of concern is that the current episode of acidification is taking place more rapidly than at any other time in the past, leaving oceanic species little time to adapt [6]. The impacts of ocean acidification on the marine food chain may have significant implications for emerging coastal economies and could cause severe food shortages for millions of people that depend upon it for sustenance which in turn could cause civil disturbances on a variety of scales.

The third climate change wild card is geoengineering. Defined as deliberate large-scale intervention in the Earth's climate system in order to moderate global warming, geoengineering methods fall into two main categories: carbon dioxide removal and solar radiation management, which reflects a small percentage of the sun's light and heat back into space [28]. Geoengineering is fast gaining attention in mainstream science discussion as a way to mitigate the warming effects of climate change in addition to regulating greenhouse gases. Joint work by the U.S. House Science and Technology Committee and the United Kingdom's House of Commons Science and Technology Committee is being conducted to explore this topic in greater detail and the Government Accountability Office recently released a 2010 report of federal government actions with respect to geoengineering. As the subject of geoengineering gains attention, there are many questions raised regarding its effects and outcomes on global and local scales. For example, the unintended consequences of geoengineering, regulation on an international scale, and effects to surrounding countries if another decides to conduct geoengineering are all scenarios that require the Navy to monitor climate intervention techniques and research for implications to its own missions.

Wild-card climate scenarios do not occur linearly and require greater monitoring and international collaborative research. These and the other near- and mid-term climate change impacts discussed will shape the Navy's approach to climate change and energy security and help it adapt to a changing climate by reducing risk associated with changing environments.

17.5 Navy and Department of Defense Initiatives

17.5.1 Guidance

To address climate change, the Navy is responding to guidance issued by the federal government, Department of Defense, as well as its own strategic guidance that calls out climate change adaptation. On the national level, Executive Order 13514, *Federal Leadership in Environmental, Energy, and Economic Performance* requires federal agencies to set goals for improving energy efficiency, resource conservation, greenhouse gas (GHG) emission reduction, water efficiency, and green procurement [21]. Within the Department of Defense (DoD), the 2010 QDR identifies climate change as one of several key geopolitical trends that may influence future conflict and directs the DoD to craft a strategic approach to energy and climate that considers the influence of climate change on shaping the operating environment, roles, and missions of the DoD, and the impact of climate change on facilities and military capabilities. With respect to the influence of climate change on installations, the QDR recognizes the significant level of environmental stewardship exercised by the Department, and directs DoD to foster efforts to assess and adapt to the impacts of climate change.

Primary Navy guidance includes the *Secretary of the Navy's (SECNAV) Energy Goals*, and the *Cooperative Strategy for twenty-first Century Seapower* (CS21). CS21 identifies climate change impacts in the Arctic as a strategic challenge, and defines Navy strategic imperatives including the prevention or mitigation of disruptions or crises, and the fostering and sustainment of cooperative relationships with more international partners. Additionally, the *Navy Strategic Plan* in support of POM 12 lists "Effects of Climate Change" as a key uncertainty in developing alternative futures. Increasing the predictability of climate change impacts will improve alternative futures planning processes and strategic guidance documents.

17.5.2 Navy Task Forces

To address the tasking set forth for the Navy regarding climate change adaptation and energy security, the U.S. Navy formed two task forces that are leveraging the U.S. Defense Department's technology and research capabilities to address climate change: Task Force Climate Change (TFCC) and Task Force Energy (TFE).

Task Force Energy is responding to the *SECNAV Energy Goals* through energy security initiatives that reduce the Navy's carbon footprint and is implementing this direction through the *Navy Energy Strategy.*

The Chief of Naval Operations, Admiral Gary Roughead, formed Task Force Climate Change in May 2009 to answer implications of climate change for national security and naval operation, to answer the question *when* in terms of Navy decisions regarding climate change, and to ensure the Navy is ready and capable to meet all mission requirements in the twenty-first century. The Navy's *Arctic* and *Climate Change Roadmaps* respond to this direction.

17.5.3 Arctic Roadmap

Because of the rapidly changing and complex environment in the Arctic, and the implications for increased maritime security presence as laid out in National Security Policy Directive-66/Homeland Security Policy Directive-25 which requires that naval forces be prepared to operation in the Arctic, the Navy chose to make the Arctic a near-term priority. As a result, the *Arctic Roadmap* was released in November 2009 to guide Navy policy, investment, action, and public discussion in the Arctic region and to build upon the Navy's extensive experience in the region. A 5-year plan, the *Arctic Roadmap* places emphasis on cooperative partnerships in joint surveys, research, search and rescue operations, maritime domain awareness, and incident response.

Key components of the *Arctic Roadmap* are already underway or completed, including a Mission Analysis and Capabilities Based Assessment of current readiness for Arctic operations. Tabletop exercises and wargaming are examining future scenarios in the Arctic and collaborative partnerships with joint, interagency, and international stakeholders are being established for hydrographic survey operations and increased environmental understanding.

17.5.4 Climate Change Roadmap

Intended as a companion document to the Navy *Arctic Roadmap* and released in May 2010, the Navy *Climate Change Roadmap* is similar in structure to the *Arctic Roadmap* in that it is a 5-year action plan with a focus on partnerships and using the best available science to support decision making and future planning. The *Climate Change Roadmap* takes a broader view of global climate change outside the Arctic and seeks to achieve five desired effects:

- The Navy is fully mission-capable through changing climatic conditions while actively contributing to national requirements for addressing climate change.

- Naval force structure and infrastructure are capable of meeting combatant commander requirements in all probable climatic conditions over the next 30 years.
- The Navy understands the timing, severity, and impact of current and projected changes in the global environment.
- The media, public, government, joint, interagency, and international community understand how and why the Navy is effectively addressing climate change.
- The Navy is recognized as a valuable joint, interagency, and international partner in responding to climate change.

Significant actions in the *Climate Change Roadmap* fall into three broad categories: Assessment and Prediction, Adaptation, and Mitigation.

17.5.4.1 Assessment and Prediction

In light of the complex and evolving climate change science and predictions, the Navy seeks to provide its leadership and decision makers a science-based, comprehensive understanding of the timing, severity, and impact of current and predicted global change on tactical, operational, and strategic (climatic) scales to inform its strategies, policies, and plans. TFCC has leveraged partnerships to engage more than 450 individuals from over 125 organizations around the world, including premier scientific, academic, and analytical organizations.

Near-term assessment and prediction efforts include fielding networked climate observation systems, such as satellite and underwater remote sensors; the development of a next-generation, coupled air-ocean-ice operational prediction system; and the deployment of a fleet of ocean gliders to contribute to national climate observation systems. The U.S. Navy will perform cooperative hydrographic and oceanographic surveys in the Bering Strait, and environmental assessments in the Arctic and in U.S. areas affected by changing precipitation patterns. Assessment and prediction efforts will ensure that Navy's missions are adaptable to the variety of climate changes predicted to occur over the next century.

17.5.4.2 Adaptation

Adaptation to climate change requires incorporation of climate change science and strategic considerations into Fleet training and planning and formal Naval training and education at the Naval Academy, Naval War College, and Naval Postgraduate School. Wargames, tabletop exercises, and limited objective experiments will be conducted to examine projected climate change impacts around the world. To achieve proper investments and ensure that they are delivered at the right time and the right cost, Navy will initiate a *Climate Change Capabilities Based Assessment (CBA)*, identify *Climate Change Science and Technology Needs,* and incorporate climate change-related guidance from the *Navy Strategic Plan* into Sponsor Program Proposals (SPPs).

The United Nations Convention on the Law of the Sea (UNCLOS) is a key tool for climate change adaptation. UNCLOS allows countries to claim jurisdiction past their exclusive economic zones based on undersea features that are considered extensions of the continental shelf. UNCLOS is of particular importance in the Arctic; the 2008 Illulissat Declaration recognizes that "the Law of the Sea is the relevant legal framework in the Arctic" and protects the national security, environmental, and economic interests of all nations. In order to ensure protection of these interests in the swiftly changing Arctic region, the Navy will continue to advocate for U.S. accession to this treaty.

As part of its adaptation strategy, the Navy is informing the media, public, government, Defense, interagency, international audiences, and other interested stakeholders regarding its policy, strategy, investments, intentions, and actions in response to climate change.

17.5.4.3 Mitigation

The Navy is dedicated to showing leadership in energy use reduction by reducing its carbon footprint and increasing its reliance on alternative fuels. The Secretary of the Navy, the Honorable Ray Mabus, has committed the Navy to making sizable progress in the next decade and directed Task Force Energy to carry out specific goals to decrease the Navy's dependence on foreign oil and increase energy security. His goals include sailing a "Great Green Fleet," reducing petroleum use, and increasing alternative energy ashore and Navy-wide. In order to achieve these goals, Task Force Energy is implementing tactical initiatives such as maritime and aviation incentivized energy conservation, improved hydrodynamics, smart voyage planning and efficient aircraft and ship systems, and efficient aircraft and ship propulsion. On the shore, net zero installations, advanced metering, auditing, smart grid technology, and improved building design and efficiency upgrades all contribute to an energy-efficient Navy. These initiatives are supported by training and awareness to educate Navy personnel of all ranks and positions about the importance of energy use reduction.

Initiatives under both the *Arctic* and *Climate Change Roadmaps* and the *Navy Energy Strategy* will meet the overall Navy objective as ready and capable in the twenty-first century.

17.6 Navy Science Needs

Significant improvements have been made over the past few decades in the collection, analysis, and interpretation of basic climate data [23]. However, as evidenced in the 2007 IPCC Report, considerable uncertainties still exist. The National Research Council notes that even as actions are taken to limit the magnitude of future climate change and adapt to its impacts, it is imperative that continued progress be made in observing all aspects of the climate system to understand climate system processes, project future evolution of the climate system, and interactions with other environmental and human systems [18]. The Navy has developed its own list of science and technology requirements that will enable it to increase its ability to assess the impacts of climate change on national security and the effects of adaptation and mitigation actions.

17.6.1 Model Resolution

Implementation of any plan is executed at the local level. Navy planners and decision makers require knowledge of future changes on scales from hours to decades at spatial resolution on the order of meters. Therefore, the Navy needs corresponding climate projection and resolution.

17.6.2 Model Physics

There is a need to improve understanding of the basic physics (including solar physics) associated with climate and the ability to model important variables (e.g. temperature, aerosol content, precipitation, winds, sea ice, sea level) at a full coupled, regional scale, including complexities that arise from the interaction of global, regional, and local processes. Models for glacier melt, sea level rise, and other water systems require the same accuracy as regional climate modeling capabilities across the same decadal time scales. Models for extreme weather events should provide data for a given location on expected frequency, intensity, and duration of these events (tropical storms, tornados, severe rains, high winds) so as to predict damage to valuable infrastructure and threats to human habitat. While the physics of carbon absorption into the ocean for ocean acidification are well modeled and verified, the impact on ecosystems and the marine food web is poorly understood. Improvement in our understanding of the biological impacts of ocean acidification are required to understand future climate change impacts to coastal communities, nations, and their fisheries.

17.6.3 Quantifying Uncertainty

To properly assess risk, decision makers require uncertainties in climate models (for temperature, precipitation, sea ice, sea level) to be quantified, and that model outputs be statistically realistic—with known confidence levels—across a decade of time. Model output should be available in probability distribution functions so as to be able to determine the risk for deviations from average values. Models should incorporate and be able to represent realistically sources of long- and short-term variation that are relevant for representing regional variability. Through quantification of uncertainty, decision makers can begin to understand where these uncertainties arise and how that may affect future decisions and investments. By reducing scientific uncertainty in model resolution and physics, the nation will be able to make the most effective and efficient investments in climate change adaptation and mitigation methods, and thereby reduce risks to national security.

17.7 Conclusion

The U.S. Navy is committed to understanding and preparing for a changing climate. With direction from the federal government, Department of Defense, and Navy as its guide, the Navy's Task Force Climate Change is implementing the Navy's *Arctic* and *Climate Change Roadmaps* to guide policy, strategy assessments, investments, and outreach to ensure that the Navy continues to set an example around the world as a force dedicated to winning wars, deterring aggression, and maintaining freedom of the seas.

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Chapter 18
Energy Security: Using Multicriteria Decision Analysis to Select Power Supply Alternatives for Small Settlements

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Abstract Selecting an effective energy strategy for military installations and small towns is a challenge given the variety of climate, geographical, economic, and social conditions as well as military mission needs. This chapter illustrates a multicriteria decision analysis (MCDA) framework for energy infrastructure planning and technology selection that can be applied to energy security, climate change impacts, and other related uncertainties. The decision model frames the problem in terms of the power plant life cycle, including plant development, commissioning, operation, and decommissioning. Metrics associated with technical, economic, sociopolitical, ecological, and human health risks are considered for each life cycle stage. These criteria and metrics are developed and quantified based on available literature data and expert judgments, and are applied to a realistic case study.

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18.1 Introduction

Energy supply selection decisions are critical to the long-term survival of military facilities and remote settlements. For military facilities, energy is an integral part of infrastructure security, since combat, surveillance, communication functions, and medical services directly depend on the reliability of a well-functioning energy supply. The loss of one infrastructure element may negatively affect other infrastructure elements, geographic areas, or economies [57]. In small, remote settlements, the lack of available backup energy supply services (for settlements on the energy grid) makes energy supply decisions crucial. In addition, the lack of trained maintenance and repair specialists may greatly increase energy downtime. For both military installations and small civilian settlements, the loss of energy could pose significant threats to human health and the environment. For instance, sewage treatment, water purification, life support, and security services may be inoperable until energy generation has been restored.

Energy supply decisions are site-specific and depend on the needs of those consuming the power. On smaller scales, regions such as cities and communities must factor in concerns such as the preservation of natural resources, economic, and political independence, and the satisfaction of long-term demands in terms of resources and outputs. Even individual buildings such as factories or hospitals must consider the risks posed by loss of power and plan accordingly. Energy strategies are dependent upon user structure, behavior, and adaptation [69]. For instance, some communities have always survived without electricity, so their energy needs are much different than those for modern military installations.

Energy source selection is generally evaluated by analyzing economic and power-output factors. While it is necessary for power supplies to be efficient from an economic and power engineering point of view, one must also consider various social factors. Considerations such as possible human health, environmental, socio-political, and ecological risks are also relevant. These energy decisions typically involve many decision makers and impact a large number of diverse stakeholders [20]. In addition, climate change may be an influential driver for selecting appropriate long-term energy strategies, both in terms of understanding and minimizing environmental impacts and taking into account future changes in climate, ecology, energy demand, and environmental regulations and policies [28].

The use of decision analysis—including multicriteria decision analysis (MCDA)—is well suited to address problems with multiple, conflicting considerations. Decision analysis helps decision makers deal with uncertainties and make tradeoffs [23, 58]. The many varieties of MCDA have been widely applied to energy decisions. For example, multi-attribute utility theory (MAUT) has been applied to energy planning in multiple instances [43, 45], including plant siting and waste disposal decisions in the nuclear industry [31, 34, 47]. The analytical hierarchy process (AHP) is another popular method for energy planning [5, 6, 40, 66], as is the related analytical network process [36]. Various outranking techniques have been utilized, such as ELECTRE [44, 52, 56] and PROMETHEE [12, 21, 67]. Each MCDA method has advantages and disadvantages in different situations, and using multiple methods may be a good strategy if time and funding permit [42, 55].

Most applications of MCDA to energy selection problems have involved large, industrial-size facilities or major cities and have not been tailored to small settlements and power facilities. Factors such as differing regulatory standards; shorter and sometimes temporary settlement lifetime durations; the lack of qualified operating staff; differing environmental impacts and resource consumptions; different power distribution strategies; potentially extreme conditions; and the cost of research, survey, and analysis all necessitate a unique approach for small, remote settlements.

In this chapter, we provide a short summary of MCDA and review and illustrate its application for solving the multidisciplinary problem of energy supply selection for small settlements. The methodology is not limited to solely technical and economic evaluations, but combines several technical, economic, and sociopolitical factors for a holistic evaluation of energy supply alternatives. This technique is applied to a case study in which power supply options are assessed for a hypothetical settlement. Wind turbines, thermal solar collectors, photovoltaic solar panels, a diesel generator, a gas turbine plant, and a small nuclear power plant are proposed as viable methods of generating energy. Expert judgment is elicited to determine the relative weights of criteria and performance of alternatives, and these data inputs drive the analysis and selection of our optimal power supply alternative.

18.1.1 Multicriteria Decision Analysis

MCDA is a class of various decision-making techniques that can integrate multiple criteria, expert judgments, and stakeholder opinions. Generally, MCDA techniques include the following steps [32]:

- Problem structuring
- Uncertainty quantification
- Preference quantification
- Evaluation of alternatives

MCDA is represented by a variety of methods including MAVT/MAUT, AHP, PROMETHEE, ELECTRE, TOPSIS [24], and SMAA [38]. Some of these methods incorporate uncertainty analysis on the basis of probability theory (for example, MAUT, SMAA), others on the basis of fuzzy set theory (for example, fuzzy-PROMETHEE), and yet others on the basis of interval mathematics (for example, INPRE, interval-SMART/SWING). Each of these different MCDA methods offers a different approach to criteria weighting and scoring. Additional information can be found in Figueira et al. [13], Belton and Stewart [3], Keeney and Raiffa [33], Saaty and Vargas [59], and Morgan and Henrion [50].

MAVT/MAUT is one of the most widely used MCDA methods [51] and can be combined with other weighting and scoring methods, including AHP [1]. The choice of method is an important step, but it does not restrict future modification of the decision model; once the problem is formulated in a decision model, other MCDA methods can resolve it as well. The structure of the decision model includes sets of criteria, alternatives, and an underlying rationale that can be reused without significant changes among the different MCDA methods.

18.2 Framing the Decision Problem

This section introduces concepts of energy supply selection in terms of the power supply life cycle and describes how MCDA can address these issues.

18.2.1 Power Supply Life Cycle

The choice of an appropriate energy source requires the analysis of a broad range of factors within each life cycle stage of the power generation facility, from the design of the facility to its decommissioning. Economic, technical, sociopolitical, environmental, and human health risk factors should be considered for each of these stages.

For simplicity we divide the entire energy facility life cycle into the following stages:

- Development
- Construction and commissioning
- Operation
- Decommissioning and utilization

The life cycle approach is widely used. Traditionally, the energy production problem is framed in terms of the fuel life cycle: extraction of raw materials, processing, transport, use, and disposal of waste [60]. However, the fuel life cycle may not always be applicable to the broad range of energy sources and management decisions. Viewing the life cycle in terms of the energy facility aligns more closely with the decisions and concerns of senior managers, such as cost, duration, and risks; each concern is described below.

18.2.1.1 Economic Criteria

As with any infrastructure development project, cost is a concern. For each stage of the life cycle, different costs are considered. For instance, in the installation and commissioning stage, costs may include delivery of components and labor for assembly and installation. In the case of fragile or expensive components, one should also factor in costs associated with insurance and spare parts. During the operation stage, costs include equipment maintenance, parts, and fuel (including transportation). The final list of expenses should be developed in conjunction with expert judgment.

As with any project, costs are subject to some uncertainty and cannot be precisely estimated due to economic fluctuations and unforeseen potential problems related to funding, technology, and labor and material supply, though these uncertainties are excluded in the present case study. Additional costs and factors related to material supply and inventory control can be found in Axsäter [2].

18.2.1.2 Duration

Similar to cost, the duration of each life cycle stage is subject to risk and uncertainty. Unforeseen problems can increase the development budget and requisite time. Expert judgment or project management tools can be helpful, but managers must pay attention to the estimation of timeframes during the development stage to ensure that deadlines will be met and the project will not be delayed. Time, especially the lead time of a product, is also taken into account in Axsäter [2].

Estimation of the lifetime of the power generation facility is another important factor in strategic planning. If the lifetime of a power generation facility is shorter than the lifetime of the settlement it powers, then it is necessary to provide a substitution period during the downtime experienced by the main power source. As opposed to reserve power generation, substitute power generation should reliably provide the average energy consumption provided by the main energy source. On the other hand, if the lifetime of a power generation facility is longer than the projected lifetime of the settlement itself, the potential reuse of the facility should be considered. For instance, a facility that can be transported to a new site and used again is preferable to a stationary one.

Cool-down time is another consideration. Nuclear power sources without onsite refueling must be left to cool down before being sent to a special facility. For example, cool-down time for the MASLWR [25] unit is about 5 years. This period of cool-down time determines the duration of the decommissioning stage.

18.2.1.3 Environmental and Human Health Risks

At each life cycle stage, various risks may have negative impacts on both the environment and human health. These risks stem from various hazards, which can be classified in five general categories: societal, system-related, technological, natural, and institutional [37]. Within these general categories, many specific hazards exist. For this exercise, we consider risks to the environment and human health arising from:

- Normal operation
- Human error
- Natural phenomena
- Sabotage
- Terrorist attack
- Implementation errors

The risks of normal operation refer to harmful physical effects due to day-to-day activities. For instance, CO_2 emissions and other substances produced by a diesel generator during normal operating conditions would be considered normal operational risks. The risks of natural phenomena include such disruptive events as earthquakes, floods, and severe weather events. Implementation errors arise from mechanical, electrical, chemical, or other defects.

Sabotage involves the intentional damage of equipment or technological processes by facility employees while terrorist attack involves intentional damage caused by third parties. The main difference is that sabotage usually strives to interrupt the normal technological processes of the facility without significant human health or environmental damage while terrorism strives for maximum damage to its victims' physical and psychological health, society, and environment. Saboteurs and terrorists typically have different knowledge and resources and—as a result—call for different technical and organizational prevention measures. Human errors are caused by internal human resources, like sabotage, but risks of accidental error can be mitigated by training programs, systemic controls, and fail-safe mechanisms.

A detailed analysis and risk assessment is necessary before arriving at a final decision. Risks for different types of facilities are commonly assessed by different methods and comparing these results can be a challenge. For example, a literature review can identify cost and power outputs for the power supply options assessment, while expert judgments may support human health and environmental risk assessments.

It should be noted that the abovementioned risks and factors are often interconnected. For example, negative public opinion may increase costs (by requiring intensive public relations efforts) and lead to higher environmental and human health risks due to additional public activity and an increased risk of sabotage and terrorist attack. For simplicity, all presented criteria are treated as independent in the case study.

18.2.1.4 Life Cycle Stage-Specific Criteria

In addition to the general criteria described above, each life cycle stage has its own unique characteristics. For example, energy consumption during the construction and decommissioning stages can be extremely important because the energy facility does not yet produce its own energy and the existing energy resources of the remote settlement may be severely limited. During the operation stage of the life cycle, power output is the most crucial factor. As the desired product of the energy facility development process, the power output must be great enough to meet the needs of the community that it serves.

Complexity is another important life cycle factor. Developing and operating a highly complex power system involves employment of highly qualified scientists, engineers, and maintenance personnel. The skilled individuals necessary for the operation, monitoring, and maintenance of the facility may be difficult and expensive to find and recruit, especially in remote locations. In this way, the availability of natural and human resources together play a role in the development process.

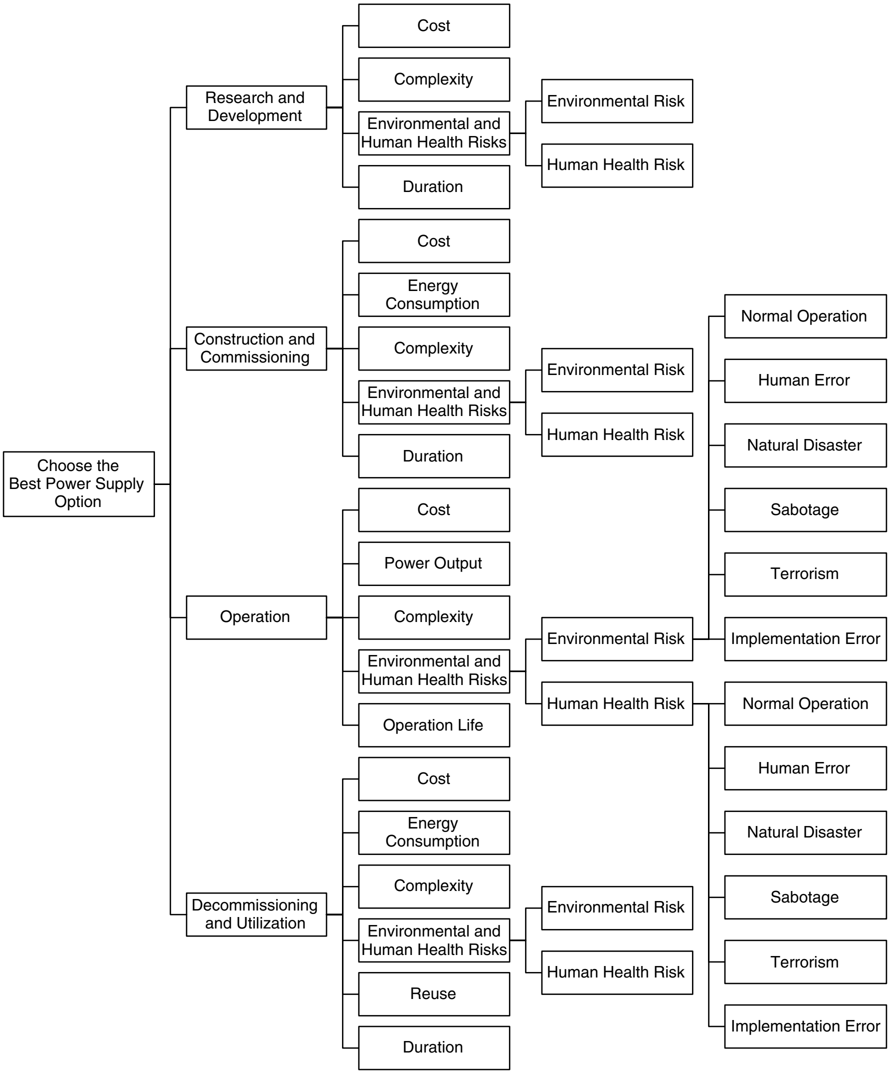

Fig. 18.1 Criteria tree for the assessment of power supply options

18.2.1.5 Criteria Tree

By taking into account each of the identified criteria, coupled with each stage of the power supply facility's life cycle, the following criteria tree is developed: (Fig. 18.1)

18.2.2 Criteria and Alternative Assessment

The set of criteria implemented in the MCDA should be complete enough to reflect the advantages and disadvantages of the considered alternatives, and each criterion should identify a particular desirable characteristic of the solution that is relevant for achieving research objectives and assessing alternatives. The assessment of alternatives against criteria is usually referenced in MCDA literature as scoring or intra-criteria assessment. The assessment of relative importance is usually referenced as weighting or inter-criteria assessment. Both are required for multicriteria decision making [11].

For scoring, values must be assigned to criteria for each alternative under consideration. These values may be explicitly quantified measurements; for example, the cost of building and installing the facility can be expressed in monetary units (e.g., millions of dollars) and the power output can be expressed in MW. On the other hand, criteria that are difficult to quantify can be expressed using an arbitrary scale (e.g., from 1 to 10; the greater value corresponding to, for instance, a higher risk), in the form of pairwise comparison (e.g., alternative A is two times better than alternative B according to criterion C), or in the form of pairwise verbal evaluations (e.g., alternative A is significantly better than alternative B according to criterion C). This verbal evaluation will subsequently be converted into numerical values following some metric(s). Another option is to quantify criteria values in terms of utility functions that can explicitly quantify a measurement or to reflect stakeholder or expert risk attitudes (i.e., regarding risk-averse, risk-neutral, or risk-seeking behavior). According to the theory behind MAVT/MAUT, the value/utility function is used for integration of different scales and units.

As for weighting, there are various methods for inter-criteria assessment, including pairwise comparisons similar to those used in scoring. Weights may be chosen on a scale of 0–100, where larger values correspond to criteria with greater relative impacts on the decision. Many times, weights are constrained so that they sum to 100. Weights are often determined by expert judgment.

For simplicity, it is often assumed that all considered criteria are additively independent. Therefore, an additive form of value aggregation for individual criteria can be used; otherwise multiplicative or mixed forms should be used [33]. For the purpose of simplicity, a linear, additive value aggregation function assuming a neutral risk attitude is used in the case study in Sect. 18.3.

18.2.3 Expert Judgments

It is often difficult or impossible to quantitatively rank certain characteristics of a system. In those instances, experts must be consulted to supplement whatever empirical data is available. Expert elicitations and literature reviews can provide both scores for alternatives and criteria weights. Experts can be interviewed in person, by phone, or online, and a number of methods and tools exist to organize and conduct expert analyses. Also, numerous bounds, frames, biases, and other issues exist when dealing with experts. Using expert judgments, metrics such as average values, extreme data points, copulas, and concordance and discordance indexes can be identified. The spread of expert judgments can be used to form interval estimates (or, randomly distributed estimates with uniform distribution can sometimes be necessary due to the difficulty in making statistically valid decisions about the distribution due to the limited quantity of experts and judgments). The obtained data allows for ranking the power supply options as well as performing sensitivity, stability, and uncertainty analysis of the decision model. Further information can be found in Wright and Bolger [68], Connolly [7], Meyer and Booker [48], Cooke [8], and Kahneman and Tversky [29].

While the evaluation of energy supply alternatives is usually technical in nature, expert preferences between criteria are generally subjective. For example, one expert may believe economic and cost factors will be the most important factors, but another may believe environmental damage will be much more significant. Subjectivity in the expert evaluations should not be equated with randomness, as each expert interprets the problem differently depending on his or her own experience and knowledge. This same subjectivity can be seen when comparing expert and layperson opinions on risks. While laypeople tend to lack the technical information about risks that experts possess, laypeople often do have rich concepts of the risks involved and the integration of expert and lay knowledge in decision making can be helpful [46, 63, 64].

The subjective expert preferences are typically presented as criteria weights and should be defined at each level of the criteria tree in a normalized relative scale. This scale might be, for example, from 1 to 100, where higher values correspond to higher criterion importance and all criteria weights sum to 100. In the following case study, criteria weights and alternatives scores were elicited from experts from many different countries (U.S., Russia, France) and organizations (U.S. Army Corps of Engineers (USACE), Brookhaven National Laboratory (BNL), Simulation Systems Limited (SSL), Obninsk State Technical University for Nuclear Power Engineering (OINPE), and CORYS).

18.3 Case Study

This section presents a simple but realistic application of prioritizing power supply alternatives for a small settlement using MCDA (specifically MAVT), expert judgments, and life cycle risk assessment. In the first stage, a list of six possible power supply options was screened for viability and reduced to a list of three options. Experts were then interviewed and asked to fill out a survey ranking the three alternatives on the criteria described in the above criteria tree. Finally, the individual responses were aggregated and analyzed to select an optimal solution for the subject settlement.

18.3.1 Hypothetical Settlement and Energy Needs

The characteristics used for this hypothetical settlement are based on Fort Bliss military facility data [14]. Fort Bliss is a U.S. Army installation located in Texas and New Mexico. The electrical power consumption in 2008 was estimated at 29 MW, the peak load reached 47 MW, and the planned consumption for 2013 is 49 MW. Fort population for 2005, including both military and civilians, was about 25,000, and there were 217 buildings with ten million square feet (about one million square meters) of total area.

Population is generally the driving factor of the required output from a power source. A linear correlation between the population and the required electric power is proposed in the paper [25], and the energy consumption at Fort Bliss corresponds well with the linear dependence. This paper shows that a population of 1,000 people consumes roughly 2–5 MW of electric power, although this depends on societal behaviors and demands (for instance, in Switzerland, there is an initiative to reach a 2,000-W society [54]). This general assumption can be used for screening power supply options by their power output, and reiterates the need to consider energy investment alternatives in terms of the geographic and societal context in which they exist.

In the case study we also make the following assumptions: the settlement location allows the use of all types of ground transportation; the risk of terrorist attack and sabotage is present due to the settlement's military affiliation; and solar and wind energy are available.

18.3.2 Proposed Energy Alternatives

Initially, several individual energy sources were proposed for the hypothetical settlement. Both renewable and exhaustible energy sources were considered, including:

- Renewable
  - Photovoltaic solar farm
  - Thermal solar collectors
  - Wind farm
- Exhaustible
  - Diesel generator
  - Gas turbine
  - Small nuclear power plant

The two types of solar energy being considered differ in method of energy conversion. Solar panels (i.e., photovoltaic cells) directly convert solar energy into electrical energy. Thermal solar collectors (i.e., solar towers and thermal solar collectors) use mirrors (heliostats) to reflect visible and infrared rays towards a collector that focuses sunlight to heat the working medium.

The power output of commercially available wind generators varies from a few hundred kW to several MW. Several manufacturers offer wind farms with total power outputs of up to hundreds of MW. A possible drawback of wind farms is environmental harm due to vibrations impacting flora and fauna including birds, fish, invertebrates, and fungi [9].

Typical diesel generators have a power range anywhere from a few kW to several hundred kW. Diesel generators can be used either as individual units or as sets of several units. Though gas prices and environmental impacts are extremely important issues, other factors including size, reliability, and maintainability allow diesel generators to remain an attractive option for backup power supply.

Gas turbine facilities use fuel—usually natural gas—to produce electricity and heat. Facility power ranges from several kW to tens of MW. The option of using natural gas makes these facilities more environmentally friendly and cost efficient than diesel generators. Gas turbines are, however, a more complex solution and require skilled staff members for operation and maintenance.

Industrial nuclear reactor design and development has trended towards a constant increase of power output over time. The power output for modern industrial nuclear power plants is hundreds of MW. According to the International Atomic Energy Agency (IAEA), reactors with output below 300 MW are classified as small reactors and nuclear reactors with power output from 300 to 700 MW are classified as medium reactors [25]. By these standards, 139 reactors of low and medium power are currently under development throughout the world. There are three primary types of small nuclear reactors: pressurized-water cooling (PWR), lead-bismuth cooling, and natrium cooling. Some additional reactors under development include gas-cooled fast reactors (GFR), very-high-temperature reactors (VHTR), supercritical water-cooled reactors (SCWR), sodium-cooled fast reactors (SFR), lead-cooled fast reactors (LFR), and molten salt reactors (MSR) [19]. Small nuclear reactors have some valuable advantages over large ones. These nuclear reactors can be an extremely efficient and environmentally friendly power supply solution, but the associated radioactive materials pose high human health and environmental risks for present and future generations. These risks are magnified by the possibilities of terrorist attack, sabotage, human error, and natural disaster. Additional information on small nuclear reactors can be found in Levchenko et al. [39], Ingersoll [26], Galena [18], Minato et al. [49], and DOE [10].

18.3.3 Initial Screening

In general, the geographic location of the settlement provides a number of screening factors:

- Availability of transportation: uninterrupted fuel supply, paved roads for heavy vehicles, transportation security

- Risk of natural disaster and terrorist attack: seismicity, hurricane, tsunami, sociopolitical instability
- Availability of renewable energy sources: solar energy, wind energy, geothermal
- Availability of the central electrical or heat supply network

In addition to these, another important screening factor is the nature of energy consumption, such as type of energy consumed (e.g., electric power or thermal energy) and daily, monthly, and seasonal peaks.

These factors can be used to screen decision alternatives (power supply options) that are not suitable for the settlement in question. This is necessary because the MCDA approach requires a manageable number of alternatives [4, 22, 59]. However, there must be a large enough number of alternatives to provide a meaningful analysis. Alternatives must be contradictory (i.e., Pareto Frontier alternatives). Simply stated, this means there are no alternatives that dominate or are dominated by others in all criteria all of the time. For example, in a case where cost and power output are the only criteria, and there are two power supply alternatives, one alternative should not be more desirable than the other in both cost and power simultaneously; in such a case the decision would be obvious, rendering MCDA unnecessary.

Solar facilities are not ideal at the selected site for many reasons. First, solar facilities require a large exposed area that must be protected from terrorists and natural disasters. Second, solar panels would not produce enough power to meet the site's requirements. Third, natural deterioration and the accumulation of grit and dirt decrease the efficiency of solar facilities over time. More importantly, the typical photovoltaic solar panel contains materials such as cadmium telluride and copper indium diselenide, which pose human health and environmental concerns and require special attention and care upon decommissioning [16, 17].

After initial screening (most of which involved simple power output totaling), three power supply options were chosen for further consideration:

- Small, 35-MW nuclear reactor (e.g., MASLWR [25])
- 32-MW gas turbine (e.g., Siemens SGT-700 [61])
- Set of ten wind turbines totaling 36 MW (e.g., Siemens SWT-3.6-107 [62])

18.3.4 Assessment of Alternatives

For simplicity, we assume that reserve and backup power supplies are fixed for all primary power supply alternatives (though, in practice, each energy supply solution should contain its own primary, reserve, and backup power supplies that could be included in the assessment). In general, the power supply needs for the selected facility necessitate the following:

- Primary >30-MW power source, which corresponds to the average consumption of power by a settlement

- Reserve power source used in case of main source failure; represented by a 32-MW gas turbine for all power supply solutions
- Backup power source for peak loads; represented by a set of diesel generators totaling 20 MW for all power supply options, which corresponds to the difference between median and peak power consumption

Due to the military-specific nature of the settlement, we assume a 100% power reserve will be needed. However, in general, due to the complex nature of power supply, the power coverage should be considered as a variable during the portfolio optimization process and should take into account the critical functions of the settlement in question.

The first step in the assessment process was to ask the experts to review the selected alternatives and criteria for completeness, significance, and interdependence. Descriptions of the alternatives, criteria, research objectives, and assumptions were given to each expert. Suggestions, remarks, and comments from the experts concerning the set of alternatives and criteria were considered and the finalized lists were incorporated into a worksheet to be completed by the experts.

The next step was to present the worksheet (Fig. 18.2) to the experts. They were asked to populate the worksheet with weights for the criteria such that each branch of the criteria tree contained weights that added up to 100. For example, each stage of the life cycle making up the main branch of the criteria tree (Research and Development, Construction and Commissioning, Operation, Decommissioning and Utilization) were given weights based on their perceived importance that added up to 100. Then, for example, the criteria comprising the Research and Development stage (Cost, Complexity, Environmental and Human Health Risks, Duration) were weighted such that they also added up to 100, and Environmental and Human Health Risks was further divided into components and weighted. This process was repeated until each criterion received a weight.

Once the weights had been entered into the worksheet, the experts were asked to score the criteria. Following the basic MCDA principles, each power supply option is presented as an alternative. In this example, the experts ranked the alternatives based on a given scale. For example, for the Operation phase, the experts scored each of the three alternatives based on their power output on a scale of 0–50, and so on for each criterion. During both steps experts were free to use any methods including mental modeling and brainstorming with other experts to clarify their judgments and estimates.

The value calculated by synthesizing all criteria and weights for a particular power supply option was used for the ranking and classification of alternatives. Rankings given by each expert can be analyzed to determine their attitudes and preferences. For expert judgments analysis, traditional methods and metrics can be used (see Sect. 18.2.3). These rankings (or some measure of central tendency based on these rankings) can aid in the final decision-making process.

Criteria Tree					Scale	Small Nuclear Reactor	Gas Turbinea	Wind Farm
Choose the Best Power Option	Research and Development	Cost			from 0 to 10, higher is worse			
		Complexity			from 0 to 10, higher is worse			
		Environmental and Human Health Risks	Environmental		from 0 to 10, higher is worse			
			Human Health		from 0 to 10, higher is worse			
		Duration			from 0 to 10, higher is worse			
	Construction and Commissioning	Cost, millions $			from 0 to 100, higher is worse			
		Energy Consumption			from 0 to 10, higher is worse			
		Complexity			from 0 to 10, higher is worse			
		Environmental and Human Health Risks	Environmental		from 0 to 10, higher is worse			
			Human Health		from 0 to 10, higher is worse			
		Duration			from 0 to 10, higher is worse			
	Operation	Cost, cents/kWh			from 0 to 5, higher is worse			
		Power Output, MW			from 0 to 50, higher is better			
		Complexity			from 0 to 10, higher is worse			
		Environmental and Human Health Risks	Environmental	Normal Operation	from 0 to 10, higher is worse			
				Human Error	from 0 to 10, higher is worse			
				Natural Disaster	from 0 to 10, higher is worse			
				Sabotage	from 0 to 10, higher is worse			
				Terrorism	from 0 to 10, higher is worse			
				Implementation Error	from 0 to 10, higher is worse			
			Human Health	Normal Operation	from 0 to 10, higher is worse			
				Human Error	from 0 to 10, higher is worse			
				Natural Disaster	from 0 to 10, higher is worse			
				Sabotage	from 0 to 10, higher is worse			
				Terrorism	from 0 to 10, higher is worse			
				Implementation Error	from 0 to 10, higher is worse			
		Operation Life			from 0 to 10, higher is better			
	Decommissioning and Utilization	Cost			from 0 to 10, higher is worse			
		Energy Consumption			from 0 to 10, higher is worse			
		Complexity			from 0 to 10, higher is worse			
		Environmental and Human Health Risks	Environmental		from 0 to 10, higher is worse			
			Human Health		from 0 to 10, higher is worse			
		Reuse			from 0 to 10, higher is better			
		Duration, years			from 0 to 5, higher is worse			

Fig. 18.2 Sample expert survey worksheet

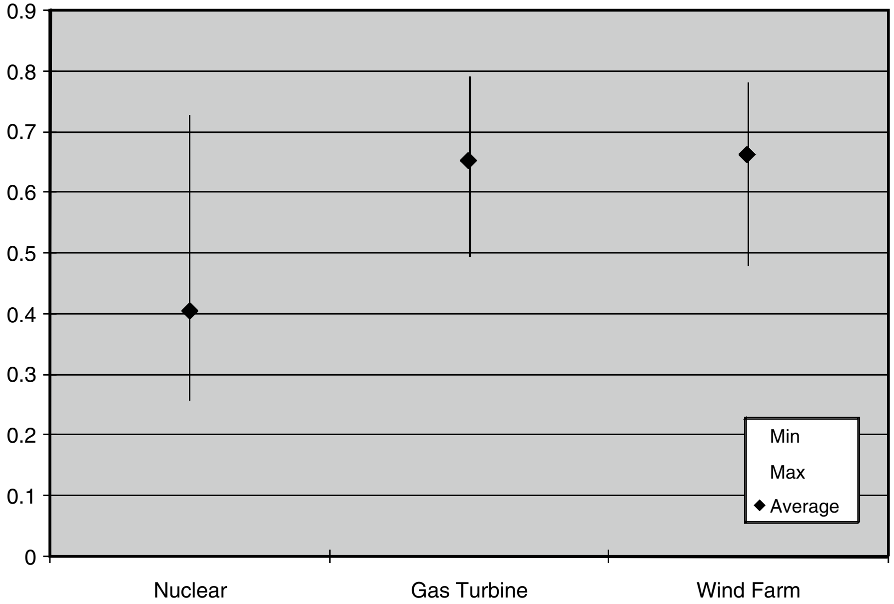

Fig. 18.3 Example total average and interval alternatives rankings

18.3.5 Analysis of Results

The output of the model yielded a virtual tie between the gas turbine and wind farm in terms of both the mean and uncertainty in the expert judgments, as shown by the error bars in Fig. 18.3. The rejection of the small nuclear reactor as a viable option was dictated by significant perceived risks to human health and environment in case of sabotage or terrorist attack.

The variation in the resulting alternative ranking is based on differences between expert judgments. Figure 18.4 shows a higher variability in scores for the nuclear reactor than for the gas turbine and the wind farm. This also illustrates how the nuclear reactor may not be the ideal alternative, as the higher variance represents more perceived uncertainties about risks and future benefits.

Correlation and concordance indexes can be used both as a test on expert judgments and as a measure of uncertainty posed by inconsistency in judgments. Sensitivity analysis, simple average and interval measures, and variation and uncertainty measures can also support reaching a final decision. If there is enough data, complex fuzzy and probabilistic uncertainty analyses can be used as well (see Sect. 18.1.1). MCDA analysis thus supports either choosing the best power supply option or screening and narrowing down choices. In the second case, the proposed approach would reduce the number of considered alternatives by ruling out low outliers, which would reduce the cost of the detailed analysis and final decision making. Moreover, the MCDA problem-structuring phase facilitates power supply portfolio analysis.

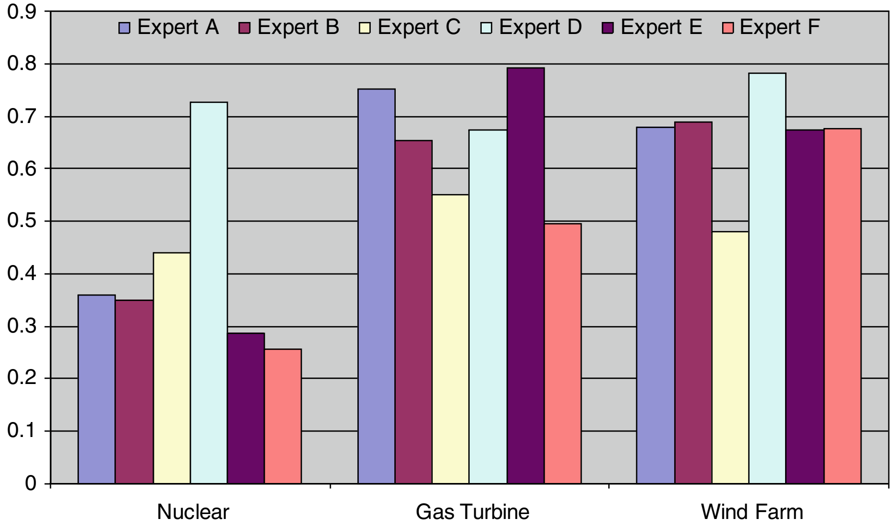

Fig. 18.4 Example alternatives rankings from six different experts

18.4 Discussion

18.4.1 Review of MCDA for Energy Planning Problems

As we have shown, energy planning can be a complex task. Energy decisions include consideration of numerous, often conflicting criteria and can involve multiple stakeholders with differing objectives and values. In addition, energy planning problems involve large amounts of uncertainty, long timeframes, and large investments [23]. These types of problems require decision-making aids, and MCDA is well suited to meet these needs [35]. As opposed to a simple cost-benefit analysis, which only assesses options on their financial merits, and comparative risk assessment (CRA), which lacks a structured method for combining performance metrics to criteria, MCDA offers a powerful and systematic methodology for evaluating alternatives based on multiple criteria and preferences [41].

No single MCDA method is a one-size-fits-all solution, and it is important to choose an appropriate method for the decision context. The method must also be transparent to users. If users do not understand how the model works and perceive it as a black box, they may not trust its output [42].

18.4.2 Incorporation of Future Technology

The proposed approach allows assessment and comparison of both existing and developing power supply options, if developing options will be available at the time

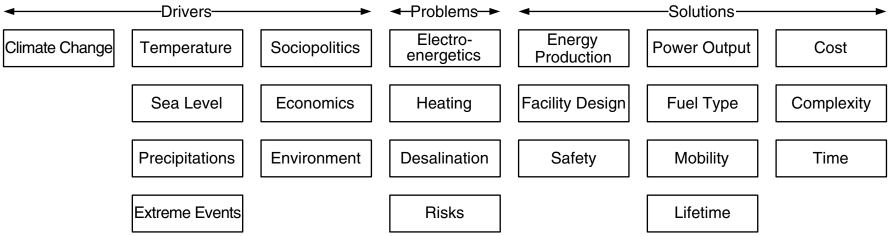

Fig. 18.5 Drivers, problems, and solutions related to energy supply and climate change

required by the project plan. Existing facilities can also be modified by investing money and time into additional research, development, and customization. The development of new and more efficient energy technologies (e.g., new types of reactors and gas turbine plants), electric devices (e.g., LED lamps for street lighting), and new tools and methods for strategic and technical decision making can be considered.

Of course the values associated with criteria such as cost, power output, and environment and human health risks for developing facilities are subject to higher degrees of uncertainty. While existing technology can be assessed based on established historical and empirical values, emerging technologies require projections and additional expert judgment to forecast power supply suitability. In these cases, the analysis of uncertainties can be extremely useful for comparing existing and developing solutions to provide important cost-benefit analyses.

18.4.3 Climate Change Adaptation

The presented approach can be easily extended to take into account climate change factors. Climate change factors impact large and small facilities differently. Climate changes impact large facilities (e.g., large power plants, industrial facilities) directly because of the long lifetime of such facilities; for small facilities (e.g., remote military settlements) the impact will be distributed in time among different facilities, which should be taken into account in the overall strategic plan. Organizations in charge of small facilities should make strategic decisions about energy technologies to pursue for investment based on how the technologies guarantee the energy security of the facility through adaptability to climate change.

Various climate change factors, adaptation and risk drivers, affected problems, and their solutions are shown in Fig. 18.5. Some factors can be integrated in the decision models directly, as criteria for alternative scoring, and others may be used as a basis for criteria weights, alternative scores, or uncertainty estimations [30]. In certain cases, climate change factors can be used as criteria for screening alternatives to eliminate infeasibilities at an early stage of the decision analysis. Another option is to modify the decision objective to follow a climate-change-based decision rule (e.g., to pick the alternative that will be most adaptable to climate change).

When thinking about adaptation as a system property, it should be applied not only to technical systems but also as a property of socio-technical systems. For example, a decision-making process that adapts itself to new criteria, alternatives, and climate change factors in choosing energy supply alternatives is as important as the options themselves. Decision-making processes and energy supply alternatives that impact and are affected by political, social, economic, technical, and environmental (e.g., climate change) factors should be considered as a complex, holistic system, or system of systems, and should be designed to be as adaptable as possible. For more information on human and environmental assimilation and accommodation, see Wright and Nebel [69], Inhelder and Piaget [27], and Park [53].

18.4.4 Uncertainty and Sensitivity Analysis

Analyzing the uncertainty and sensitivity of results is an important step in any decision process, and uncertainty can be incorporated into MCDA analysis through statistical uncertainty-propagation methods. (For more on uncertainty analysis in MCDA, see Stewart [65] and Morgan and Henrion [50]).

Sensitivity analysis can be considered a type of uncertainty analysis. Sensitivity analysis allows evaluation of the sensitivity of the final decision to the different alternatives' scores or criteria weights. For example, if a small shift in expert weighting from economic criteria to power-output criteria changes the ranking of power supply alternatives, then the decision model may be seen as unstable. Additional analyses, including problem restructuring and reassessment of scores and weights, would then be recommended. Sensitivity analysis can also provide upper and lower limits for certain criteria. For instance, it is possible, through sensitivity analysis, to increase the score of a criterion, such as cost, until the rankings change. In this way, one could identify the maximum amount one would be willing to pay for an alternative before another alternative becomes more preferable. For more information on sensitivity analysis, see French [15].

18.5 Conclusion

The complex task of energy supply selection calls for rational decision making. We have shown that techniques based on an MCDA framework can incorporate various criteria and expert judgments and compare different alternatives in the context of choosing the best power supply option for a remote settlement in terms of the plant life cycle.

One of the greatest assets of an MCDA-based decision approach is that it is robust, scalable, and capable of integrating many extensions, including life cycle analysis, portfolio analysis, incorporation of future technologies and climate change impacts, utility theory, and probabilistic uncertainties and sensitivity analysis, if needed.

MCDA techniques can utilize many different scoring and weighting techniques and are applicable to a wide range of problems. Given current energy, technology, and climate-change concerns, decision makers face a multitude of alternatives and factors that cannot be suitably evaluated with traditional financial methods. MCDA is a rigorous, quantitative tool that can assist decision makers in making transparent and defensible decisions.

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Chapter 19
Climate Change Impacts and Adaptation on CONUS Military Installations

R.C. Lozar, M.D. Hiett, and J.D. Westervelt

Abstract Military installations must be maintained and managed to provide appropriate training and testing opportunities. As climate changes, natural areas on installations may shift, and the costs to maintain training and testing areas may change. This chapter looks across continental U.S. (CONUS) installations with respect to the habitat and erosion consequences associated with climate forecasts from four Global Climate Models (GCMs). Habitat is important from two perspectives: its ability to support training and testing, and its capacity to meet federal requirements regarding the maintenance of listed threatened and endangered species. That capacity can change due to shifts in weather patterns, flooding, drought potential, and annual temperature patterns. With substantial change, species can be directly affected by invasive species, loss and fragmentation of habitat, or increased disease and predation. Population losses for these species can result in loss of training lands and/or time.

Additionally, climate change might result in changes in erosion patterns and intensity, which can also directly affect training. This chapter begins an exploration of how climate change forecasts can be converted to forecasts regarding potential challenges to habitats and species and potential impacts on erosion at each of about 130 CONUS installations. The chapter concludes with recommendations on how to adapt to these changes.

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19.1 Introduction

According to the 2007 Fourth Assessment Report by the Intergovernmental Panel on Climate Change [14], global surface temperature increased 0.6°C ± 0.2°C during the twentieth century [16]. Most of the observed temperature increase since the middle of the twentieth century has been caused by an anthropogenic increase in concentrations of greenhouse gases. Climate model projections summarized in the 2007 IPCC report indicate that global surface temperature is likely to rise between 1.1 and 6.4°C during the twenty-first century [16].

In February 2010, the President's Council on Environmental Quality (CEQ) issued draft guidance to all federal agencies that climate change should be considered while evaluating the environmental consequences associated with federal actions under the National Environmental Policy Act (NEPA) [26]. This new guidance extends the issues to be considered to include greenhouse gas (GHG) emissions and the effect of climate change on resources, ecosystems, or human communities. As with other agencies, the effects of climate change are expected to impact continental U.S. (CONUS) military installations. In particular, Army installations have large land-based range areas used for testing, training, or maneuvers. Climate change has the potential to affect at least three concerns of most interior continental installations:

- Erosional characteristics
- The management of threatened and endangered species (TES)
- The appearance and increase of noxious invasive species

To explore these and other issues, the U.S. Army Corps of Engineers (USACE) Engineering Research and Development Center (ERDC) has set aside a portion of funding from The Center Directed Research Program to build capability and research capacity focused on military installation management.[1] The ERDC is pursuing five major tasks as a part of the parent project from which this chapter was derived:

1. Design of analytical system architecture
2. Climate downscaling, calibration, and integration with consequence models
3. Hydrologic impacts of climate change
4. Development of ecological process models
5. Development of integrated risk and decision analysis framework

The research in this chapter represents the initial action for Task 4: Ecological Process Models. Specifically, we identify the Army installations that show the greatest

[1] Much of the following discussion is taken directly from the research proposal, the funds from which support this portion of the research initiative: Proposal CDR SOW 3-1-10, *Integrated Modeling and Risk Analysis for the Environmental Consequences of Climate Change: A Framework for Assessing the Environmental Effects of Climate Change for the Military*, Statement of work for the U.S. Army Corps of Engineers, Engineering Research and Development Center. 1 March 2010.

risk of severe effects due (at least in part) to climate change. Most literature examining military installations has dealt with the effect of rising sea levels on coastal areas, a concern more important to Navy and Marine interests than for Army installations. Land managers deal with their lands in the context of the ecosystem in which they reside. What happens if that ecosystem changes? How does a land manager then care for those changing lands while still supporting his/her mission?

19.1.1 Objective

The objective of this chapter is to provide a preliminary evaluation of more than 100 CONUS Army installations that examines the effects of forecasted climate change on ecosystems and related concerns (erosion, TES, and invasive species). We provide a rank order of the impacted installations and broad conclusions as to the changes that will be required for installations to carry on their responsibilities.

19.1.2 Approach

We provide a background review of the Department of Defense (DoD) and Army documents and procedures relating to climate change issues in Sect. 19.2 and a review of historic ecosystem characterizations in Sect. 19.3. Section 19.4 consists of a broad review of climate change research—particularly the predicted spatial distribution of expected changes. In Sect. 19.5, we describe the data sets and the procedures used in our evaluation of climate change, ecosystems, erosion, TES, and invasive species effects. Time horizons for these data sets are the years 2000 and 2099. Finally, in Sect. 19.6 we provide a rank ordering of the climate effects on over 100 Army installations, compare the rankings, and draw preliminary conclusions.

19.2 Climate Change and the Military

In February of 2010 the *Quadrennial Defense Review* (QDR) [26] was the first DoD publication to address the issue of the "Growing Need to Consider Risks and Response Strategies for Climate Change." In this document, the DoD explicitly acknowledges that climate change will likely affect the nature and scope of future military missions while also impacting training and testing assets of military installations. Accordingly, the military must:

- Reliably assess the causes and consequences of climate change.
- Arrive at a coherent and robust understanding of a broad range of possible response options that minimize adverse environmental consequence and maximize the likelihood of mission success around the globe.

19.2.1 Framework for Assessing the Environmental Effects of Climate Change for the Military

Considerations dealing with climate change prediction presuppose an analysis and evaluation capability that is far from trivial in design, scope, and purpose. In the military realm, for example, mission, geophysical space/terrain, and human agency are tightly interwoven. Risk and uncertainty are endemic features of the climate change problem. Consequently, decision makers require sophisticated tools for effectively managing risk as part of their decision evaluation and implementation processes. Ecological modeling is an important aspect of those tools.

The first step toward the ecological modeling process is that of a national-scale Ecological Impact Analysis. Ecosystems in the CONUS have been categorized, defined, and located through analyses conducted by Bailey, Omernik, and the U.S. Geological Survey (USGS) Gap Analysis Program (GAP) (among others).

Using national-scale climate change forecasts for temperature and precipitation, we ran our model against various Global Climate Model (GCM) scenarios to generate maps suggesting how national-scale ecosystem patterns might shift. The resulting suite of maps provided a range of forecasts for significant ecosystem change at all locations across the country, including military installations.

Climate change will push existing ecosystems towards thresholds where the current systems will be restructured to the point of replacement with significantly altered or "novel" ecosystems [16]. Currently, military installation lands are managed to maintain their present ecosystem. Under the climate change paradigm, future land management intensity and costs will increase unless we develop a better understanding of the potential character of ecosystem transformations.

Key questions facing installations in the years to come include:

- Which installations are at greatest risk for habitat disruption that is partially or fully driven by climate change?
- Where will disruptions involve ecoregion shifts?
- How are habitats at installations likely to change and when might these changes occur?
- Should installations invest in maintaining current ecosystem states?
- How will sensitive habitats supporting TES change?

19.3 Historic Ecosystem Characterizations

First published in 1983, Dr. Robert G. Bailey's ecoregion classification and its various improvements [1, 2, 3, 4, 5] became a standard reference in the field of ecology. A four-level hierarchy is used to differentiate the ecoregions. Domains (the broadest subdivision) are groups of related climates differentiated based on precipitation and temperature. Sections are the finest subdivision and are based on terrain features [30].

James M. Omernik developed his ecoregion classifications [24] while working with the U.S. Environmental Protection Agency's (USEPA's) National Health and Environmental Effects Research Laboratory in Corvallis, Oregon. The Omernik ecoregion system is based on a four-level hierarchy and considers the spatial patterns of both the living and non-living components of the region, such as geology, physiography, vegetation, climate, soils, land use, wildlife, water quality, and hydrology. Level I divides North America into 15 broad ecoregions appropriate for analysis at a global or intercontinental scale. Level III uses 194 ecoregions to describe North America. Of the 194, 84 Level III regions were used in this analysis.

USGS GAP has recently derived ecological characterizations for the U.S. The latest version of the land cover map contains 551 ecological systems. The map combines data from previous GAP projects in the southwest, southeast, and northwest U.S. with data from the LANDFIRE project compiled by Landscape. The technologically derived GAP data is used in this study as if it were an ecosystem map.

The Hargrove/Hoffman map of ecosystems was first presented in their 2004 paper [35]. Multivariate clustering is based on fine spatial resolution maps of elevation, temperature, precipitation, soil characteristics, and solar inputs. Finer divisions highlight local condition gradients, ecotones, and clines. By creating an objective ecoregion classification, the ecoregion concept is removed from the limitations of human subjectivity, making possible a new array of useful derivative products. We used this as a basis to classify multiple geographic areas into a single common set of quantitative GAP ecoregions as a basis to portray climatic or environmental changes geographically in terms of current conditions. In the Hargrove data upon which we based the GAP portion of this research, we used a newly generated data set based on 17 variables that delineate 30,000 ecoregions across the globe.

19.4 Climate Change Modeling Review

19.4.1 General Background to Climate Modeling

Climatic change as an area of concern dates back to the 1960s [18]. Many individuals and groups have been trying to objectively understand the direction of climatic change and many models have been developed.[2] The best respected models all generate predictions based on a set of conventions disseminated through the IPCC. Such standardization is meant to facilitate comparison between models.

[2] The best known of which include National Center for Atmospheric Research (NCAR, in Boulder, Colorado, USA); the Geophysical Fluid Dynamics Laboratory (GFDL, in Princeton, New Jersey, USA); the Hadley Centre for Climate Prediction and Research (in Exeter, UK); the Max Planck Institute for Meteorology in Hamburg, Germany; and the Institut Pierre-Simon Laplace (IPSL in Paris, France).

Table 19.1 The four SRES families of the fourth assessment report vs. projected global average surface warming until 2100

AR4	More economic focus	More environmental focus
Globalization (homogeneous world)	A1 Rapid economic growth 1.4–6.4°C	B1 Global environmental sustainability 1.1–2.9°C
Regionalization (heterogeneous world)	A2 Regionally oriented economic development 2.0–5.4°C	B2 Local environmental sustainability 1.4–3.8°C

As the predictive capabilities of climatic models are refined, discrepancies between them grow less significant. However, enough variation still exists so that critics are able to use differences between the models to exaggerate the differences within climatic research. To minimize such confusion, the IPCC acts as a coordinating organization and its reports are intended to reflect the scientific consensus among the experts in the field. That consensus includes items that should no longer be controversial by any knowledgeable organizations [14]:

- Climate change is occurring.
- Variations in temperature and precipitation occur locally.
- Globally, the planet Earth is warming.

19.4.2 The Scenarios upon Which Climate Modeling Efforts Are Based

One of the primary responsibilities of the IPCC is the arrangement of a series of standard future scenarios to assist with coordination and comparison between modeling results. This international standard set of scenario types is named after The Special Report on Emissions Scenarios (SRES) [27]. The SRES was a report prepared by the IPCC for the Third Assessment Report (TAR) in 2001 on future emission scenarios to be used for driving GCMs to develop climate change scenarios. The SRES were also used for the Fourth Assessment Report (AR4) in 2007. Table 19.1 lists four scenario families.

19.4.3 The Major Climate Models

Since the 1990s the international scientific climate change community has participated in a series of efforts to carry out major, mostly coordinated attempts to exercise their best available modeling capabilities under similar sets of SRES.

Table 19.2 SRES Scenario runs for AR4 (status of data: August 2006)

Center	Country	Acronym	Model
Beijing Climate Center	China	BCC	CM1
Bjerknes Centre for Climate Research	Norway	BCCR	BCM2.0
Canadian Center for Climate Modelling and Analysis	Canada	CCCma	CGCM3 (T47 resolution) CGCM3 (T63 resolution)
Centre National de Recherches Meteorologiques	France	CNRM	CM3
Australia's Commonwealth Scientific and Industrial Research Organization	Australia	CSIRO	Mk3.0
Max-Planck-Institut for Meteorology	Germany	MPI-M	ECHAM5-OM
Meteorological Institute, University of Bonn, Germany		MIUB	ECHO-G
Meteorological Research Institute of KMA, Korea		METRI	
Model and Data Groupe at MPI-M, Germany		M&D	
Institute of Atmospheric Physics	China	LASG	FGOALS-g1.0
Geophysical Fluid Dynamics Laboratory	USA	GFDL	CM2.0 CM2.1
Goddard Institute for Space Studies	USA	GISS	AOM E-H E-R
Institute for Numerical Mathematics	Russia	INM	CM3.0
Institut Pierre Simon Laplace	France	IPSL	CM4
National Institute for Environmental Studies	Japan	NIES	MIROC3.2 hires MIROC3.2 medres
Meteorological Research Institute	Japan	MRI	CGCM2.3.2
National Centre for Atmospheric Research	USA	NCAR	PCM CCSM3
UK Met. Office	UK	UKMO	HadCM3 HadGEM1
National Institute of Geophysics and Volcanology	Italy	INGV	SXG 2005

The most recent is the IPCC's Fourth Assessment Report (AR4) mentioned above. In this study, we used AR4 model results. Table 19.2 lists the major players in the AR4 campaign and the status of their models. Those used to support the work in this study are shaded.

Figure 19.1 displays the 16 models for temperatures and precipitation for an area in the southeast U.S. The data shown in Fig. 19.1 underscores a few ideas that are evident when one compares different models using any of a large number of characteristics:

- Differences between models do exist.
- The degree of variation between models is in terms of a few percent, not orders of magnitude.

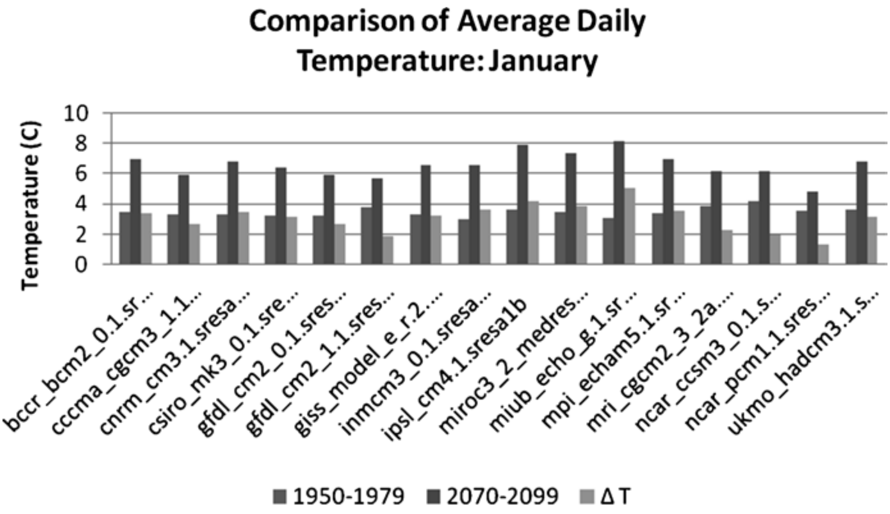

Fig. 19.1 Comparison of the 16 models for temperatures and precipitation data for the southeast U.S. quadrant

- Variations exist, but all models agree that warming will occur; i.e., no model generates a cooling trend.
- Similarities among the major models are more notable than their differences.

We wished to ensure that the models we used represented a range. The Canadian [31] and Australian [11, 32] models form the basis for the temperature, precipitation, and ecosystem change analyses. The Hadley [10] and PCM [15, 33] models are used as the basis for the Hargrove/GAP ecosystem change analysis.

19.4.4 Downscaled Climate Projections

Most climatic models output their results at a spatial resolution of approximately 3° square. This is roughly the coverage of a state in the U.S. To assess climate impacts at the regional scale required for ecological modeling, "downscaled" data was necessary. Downscaling through the application of dynamic and statistical modeling refines climate model results to specific regions based on more local concerns such as topography, surface winds, evaporation, and local precipitation [29]. Downscaling climate scenarios has resulted in spatial data available at a 1/8-degree resolution (about 13 km, Fig. 19.2) from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model dataset (referenced in the IPCC AR4).

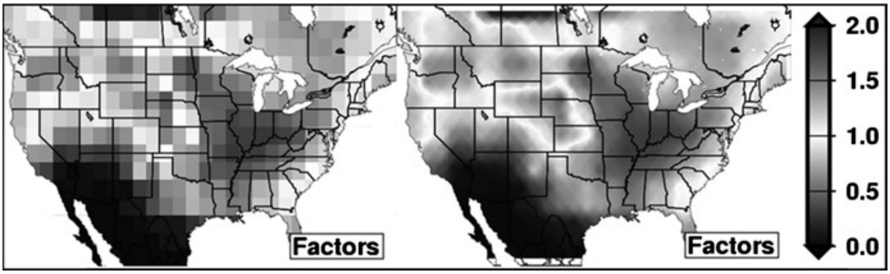

Fig. 19.2 Comparison of normal climate model output and bias corrected downscaled data for the same factor

19.5 Descriptions of Analysis Procedures to Generate Predictive Map Data Sets

19.5.1 Inputs to the Analysis

The first input to our analysis was the ecological characterization of the "current" situation. These are the spatial definitions of ecosystems: *Bailey's Ecoregions*, *Omernik's Ecosystems*, and the USGS GAP supported by the Hargrove/Hoffman *Multivariate Methods for Ecoregions Visualization*. The second input was the Climatic Change Data that was used as the basis of the "future" situation. We chose to use four standard models for the characterization of the 2,100 state of affairs. The third input is the scenarios adopted (see Scenario family's Table 19.1). We have used these inputs in the following ecosystem-climate-scenario combinations:

1. Bailey's Ecoregions using the:
   (a) *Canadian GCM3.1 model* [6]
      (i) Scenario A1b, *Globalized Rapid Economic Growth* (Fig. 19.3)
      (ii) Scenario B1, *Globalized Environmental Sustainability*
   (b) Australian Model, Scenario A1b, *Globalized Rapid Economic Growth*.
2. Omernik's Ecoregions using the:
   (a) *Canadian GCM3.1 model*
      (i) Scenario A1b, *Globalized Rapid Economic Growth*
      (ii) Scenario B1, *Globalized Environmental Sustainability*
   (b) Australian Model, Scenario A1b, *Globalized Rapid Economic Growth*.
3. GAP Analysis based on the Hargrove/Hoffman Ecoregions using the:
   (a) *HadCM3model*
      (i) Scenario A1, *Globalized Rapid Economic Growth*
      (ii) Scenario B1, *Globalized Environmental Sustainability*

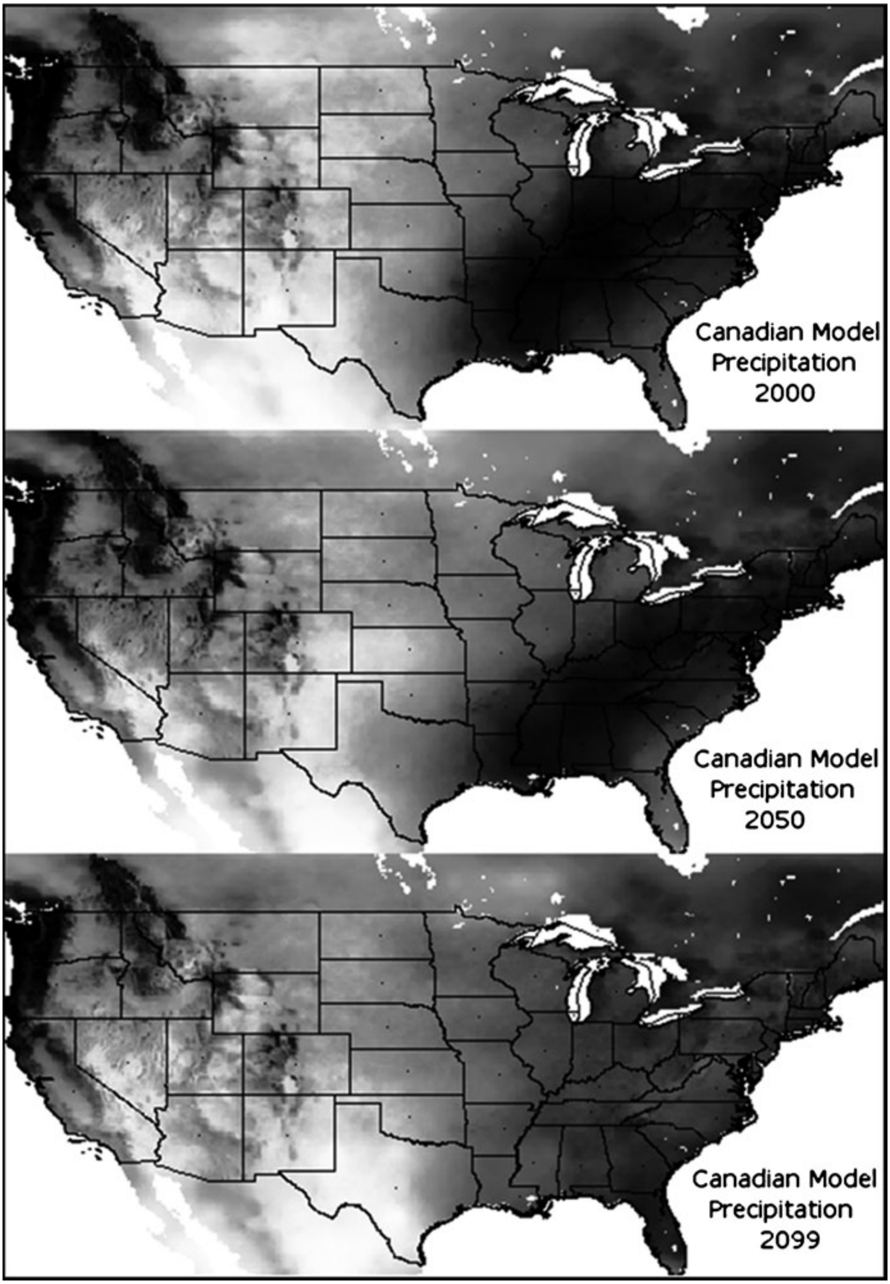

Fig. 19.3 General view of raw Canadian model precipitation (Canadian Model 3_1.5 Scenario A1b). The very wet area along the Ohio Valley disappears, Western Texas becomes drier, and southern Arizona becomes slightly less arid

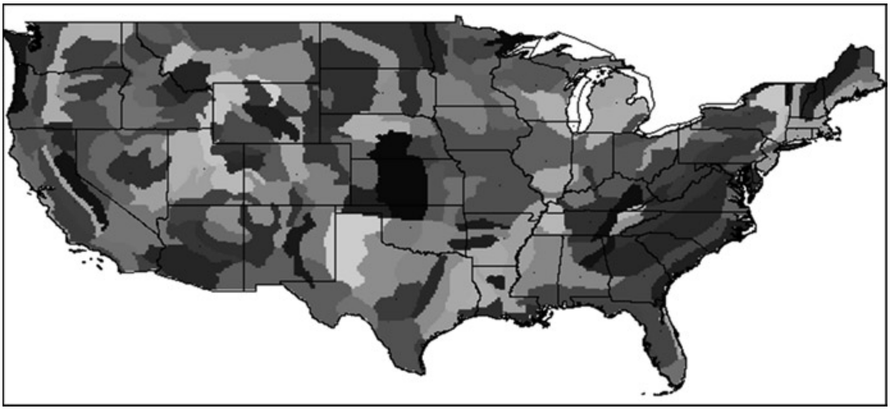

Fig. 19.4 Bailey's original regions

(b) *NCAR PCM model* [7]

(i) Scenario A1, *Globalized Rapid Economic Growth*
(ii) Scenario B1, *Globalized Environmental Sustainability*.

4. Erosion Analysis based on Soil and Topography using a:

(a) *Statistical combination of eight climate models*[3]

(i) Scenario A1b, *Globalized Rapid Economic Growth*.

19.5.2 Approach to Ecosystem Manipulation of the Climatic Change Prediction Data

The Bailey map was generated by experts who drew polygon shapes on a paper map. This means that although there was good knowledge behind the work, the map was also generalized. Realizing this, our task was to show how climatic change affects those ecosystems. We chose to base our work on the well known version from the U.S. Digital Atlas [20] (called ecoregp075) with the units at their most detailed level, "Sections."

We wished to follow changes in the ecosystem over time so it was necessary to correlate the Bailey's map (Fig. 19.4) with those items that would change over time to 2099 in the climate models, namely temperature and precipitation. Correlation statistics were generated between the single Temperature/Precipitation and Ecoregion maps. Finally, those categories most in common with both were used to reclassify the single Temperature/Precipitation map into an equivalent ecosystem

[3] Precipitation intensity dataset was provided by Dr. Claudia Tebaldi, a research scientist with Climate Central, Inc. The dataset is nearly identical to the one used in Meehl et al [19]. The primary difference is this dataset includes eight models whereas the data used in the article included nine.

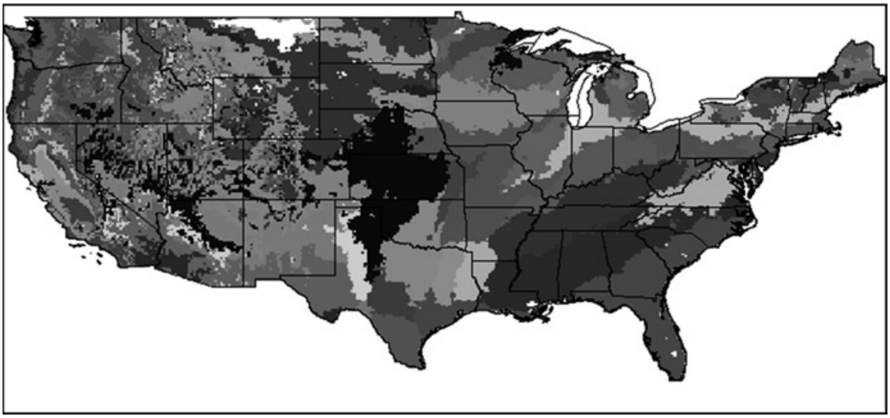

Fig. 19.5 Revised Bailey's ecoregions based on 2000 temperature and precipitation and using the same gray scale as above (CM3_1.5 Scenario A1b)

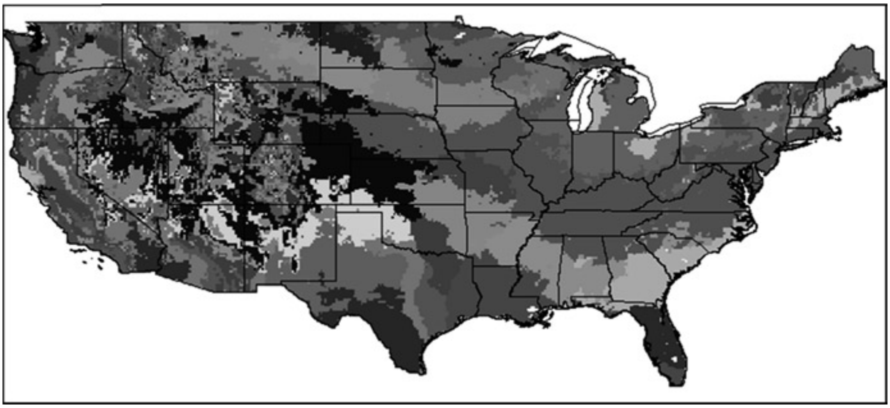

Fig. 19.6 Bailey's ecoregions based on 2099 temperature and precipitation and using the same gray scale (CM3_1.5 Scenario B1)

map (Fig. 19.5) for the revised Bailey's map. The revised Bailey's map could then be correlated with changing climate data to project changes over time.

Without question, the two are not exactly the same, but the latter matches the former roughly, and more importantly it allowed us to follow ecosystem changes due to climatic change for Army installations (Fig. 19.6).

We used a similar procedure to roughly follow the changes one would expect in Omernik's definition of ecosystems.

Although it is believed that the procedure is sound, the fact that we were only able to generate 78 imagery classes covering the whole U.S. is a severe limiting factor. Each of these 78 class regions covered an area close to the size of an average state.

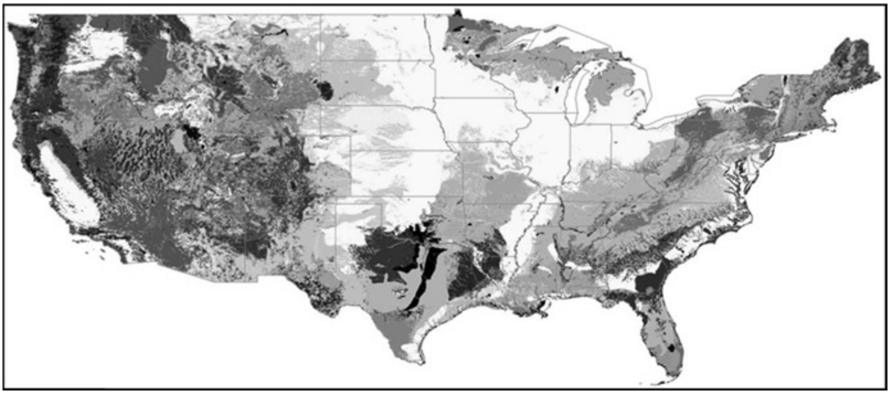

Fig. 19.7 Hargrove's global ecosystem map reclassified to GAP categories as used in this report

In terms of the Hargrove data, we developed future habitat maps for the CONUS based on forecasts from GCMs and habitat classifications developed by the GAP program as correlated with the Hargrove maps (see Fig. 19.7) based on the Hadley Centre model (HadCM3) and the National Center for Atmospheric Research (NCAR) Parallel Climate Model. The Hargrove approach applies the Multivariate Geographic Clustering (MGC) procedure simultaneously using nine sets representing the current global state and the eight forecasted future states. Each ecoregion map included 30,000 unique clusters representing eco-units based on 17 input map layers. With these we reclassified the data to generate our analyses.

It is useful to characterize the similarities and differences between the Bailey/Omernik procedure and the procedure used to generate the Hargrove data. The Hargove data was also developed using the Unsupervised Imagery Classifier technique. However, Hargrove's work has been carried out over a longer time horizon so it is much more detailed. He standardized his resolution at 1 km while our best climatic data is at 1/8th degree. He used 17 variables to make 30,000 categories across the world while we used only two to make 78 categories over the CONUS area. We both normalized our imagery layers before the analysis was run so that each layer had equal weight. He used the Hadley and PCM models for his predictions while we used the Canadian and CIRSO models. We both used the A1 and B1 scenarios for our work.

19.5.3 Approach to Climatic Change Effects on Erosion

The problem in estimating erosion potential is that it increases dramatically as rainfall intensity increases; therefore, change in overall precipitation does not provide enough information.

It is widely agreed that global climate change will lead to fluctuations in both annual precipitation and intensity. In 2003, a Soil and Water Conservation Society report concluded that, "upward trends in total precipitation, coupled with a bias toward more extreme precipitation events, are indicated in both simulated and observed climate regimes" [28].

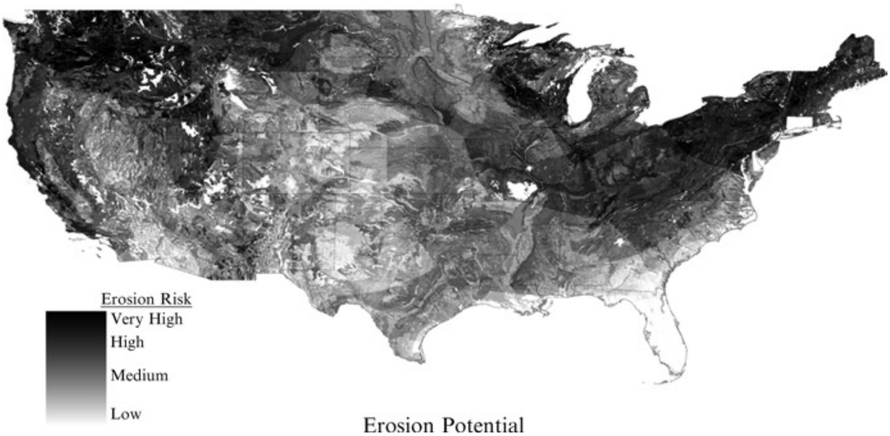

Fig. 19.8 Resultant erosion analysis showing potential using the high K-factor

Studies that examine precipitation patterns from the twentieth century consistently reaffirm the IPCC reports of increasingly variable precipitation [17]. The variable precipitation pattern of the twentieth century is expected to continue (or even accelerate) as both the number of days with precipitation and the percentage of precipitation in the form of extreme (or heavy) rainfall events increase [9, 21]. As the global climate changes in the twenty-first century, the bulk of current research suggests that precipitation regimes will become increasingly extreme, leading to longer periods of drought followed by more intense rainfall events and resulting in greater risk of erosion [25, 34, 36]. Vegetative land cover will suffer during the drought periods and will not provide sufficient erosion resistance during storms [22].

For this analysis, we gathered nationwide data for three factors: slope, soils, and projected precipitation intensity due to climate change. Slope and soil conditions represent present conditions at installation sites and precipitation intensity change represents the estimated impact of global climate change on the rainfall patterns in CONUS.

We made an effort to include as many aspects of the Revised Universal Soil Loss Equation (RUSLE) in our analysis as possible. Our soil erodibility data came from the U.S. Department of Agriculture (USDA) soils K-factor input. Specifically, the K-factor indicates the susceptibility of soil to sheet and rill erosion by water. We modeled erosion using both "High" (Fig. 19.8) and "Low" versions of the K-factor, in part to see the sensitivity of the erosion results to slight variations in this important input. In our results, a few installations changed their status by one rating level; this was deemed not significant to the overall results of the erosion studies.

The raw precipitation intensity data used in this is a comparison between the average precipitation intensity at the end of the twentieth century (1980–1999) and the average projected precipitation intensity at the end of the twenty-first century (2080–2099).[4]

[4] The raw data was generously shared by Dr. Claudia Tebaldi, a research scientist for Climate Central, Inc. The dataset is nearly identical to the one used in Meehl, et al [19]. The primary difference is this dataset includes eight models whereas the data used in the article included nine.

Table 19.3 Summary of known invasive species

Installation	Number of invasive Sp.
Fort Benning	177
Fort Bliss	178
Fort Bragg	217
Fort Campbell	127
Fort Carson	54
Fort Drum	185
Fort Hood	196
Fort Hunter Liggett	135
National Training Center and Fort Irwin	45
Fort Knox	114
Fort Leonard Wood	182
Fort Lewis	195
Fort Polk	72
Fort Riley	182
Fort Rucker	130
Fort Sill	167
Fort Stewart	184
Fort Wainwright	52

We elected to use a standard deviations measure to categorize the data, as that is the norm for displaying these projected precipitation intensity trends.

In the final erosion risk analysis, we added three input datasets together. Locations with higher sums represented higher total values in the input datasets and thus higher potential for future erosion due to climate change (see Fig. 19.8).

19.5.4 Threatened and Endangered Species

TES are one of the Army's highest cost-to-manage concerns. The Army identified 188 TES on 99 installations for fiscal year 2007 (FY07) [13]. During FY07, the Army spent $45.09 million on TES management plus additional amounts for work-arounds and avoidance in military operations or construction. The 10 installations with the highest reportable expenses accounted for 68% of the Army's total reportable expenses. The red-cockaded woodpecker (resident in the southeastern U.S.) and desert tortoise (resident in the southwestern U.S.) required the most expenditure of all species—not just in FY07, but also cumulatively for the past 5 years.

19.5.5 Invasive Species

Invasive species management costs installations a good deal of time, labor, and money. Our resource for this subject was the Army report, *U.S. Army Floristic Inventories* [12]. From this report, installations were extracted, and then the number of invasive species/installation was summarized (Table 19.3). Invasive species populations are listed at only 18 installations. It is assumed that these are the only installations for which surveys have been done. From this limited data, we can say that, where surveys have been done, invasives were found to be common, often ranging into the hundreds of species per installation. This finding becomes the base for dealing with the issue in terms of climate change.

19.6 Analyses and Results of Climate Change Effects on Ecosystems, Erosion, TES, and Invasive Species at Army Installations

This section identifies individual CONUS Army installations most highly effected by climate change, largely at two time horizons, 2000 and 2099 (data is available for all years from 1950 to 2099).

19.6.1 Precipitation

Table 19.4 lists the 10 Army installations that show the greatest precipitation change between 2000 and 2099 by the Canadian Scenario A1b, *Globalized Rapid Economic Growth*.

Table 19.5 lists the 10 Army installations that show the greatest precipitation change between 2000 and 2099 by the Canadian Scenario B1, *Globalized Environmental Sustainability*.

Interestingly, Table 19.5 also lists 6 out of 10 installations included in Table 19.4. This indicates a high agreement of what will happen at these locations no matter what scenario is adopted; they are simply the most likely to be highly impacted.

It is interesting to note that, in the Canadian Scenario B1, some installations show increased precipitation; these are exactly the installations not listed in Table 19.4.

Table 19.6 lists those installations that experience the greatest change in the Australian Model, Scenario A1b, *Globalized Rapid Economic Growth*.

Those installations above in the Canadian Model, Scenario B1, *Globalized Environmental Sustainability*, predicted to have the greatest increase in precipitation (Table 19.5) appear in the Australian Model, Scenario A1b (Table 19.6) as well. Once again, this list of the top 8% in precipitation change among 128 installations indicates that there is great stability in the precipitation predictions, particularly for Redstone Arsenal, which shows up in all three models.

As a matter of interest, we checked the rankings of the six greatest predicted changes in precipitation from the first two lists against their rankings in our comprehensive listing. Of these, only Camp Atterbury and Fort Knox do not belong in the top 50%. From the map shown in Fig. 19.9, it is apparent that these are the two most northerly of the highly impacted installations. The Australian model tends to place the larger changes further to the south as all the other installations in the above list still belong in the top 50% change category.

Table 19.4 Greatest precipitation change according to the Canadian Scenario A1b

Installation	Canadian Scenario A1b, Prcp 20–99 change in mm/day
Fort Knox	−8.1
Fort Campbell	−7.8
Milan Arsenal and Wildlife Management Area	−6.4
Camp Atterbury Military Reservation	−6.3
Mount Baker Helicopter Training Area	−6.3
Redstone Arsenal	−5.6
Pine Bluff Arsenal	−5.0
Snoqualmie National Forest	−4.8
Camp Joseph T. Robinson	−4.1
Picatinny Arsenal	−3.8

Table 19.5 Greatest precipitation change according to the Canadian Scenario B1

Installation	Canadian Scenario B1, Prcp 20–99 change in mm/day
Fort Campbell	−9.0
Milan Arsenal and Wildlife Management Area	−8.5
Fort Knox	−7.9
Hunter-Liggett Military Reservation	7.7
Redstone Arsenal	−7.0
Hunter-Liggett Military Reservation	6.5
Pine Bluff Arsenal	−6.5
Camp Atterbury Military Reservation	−5.9
Presidio of Monterey	5.7
Camp Roberts Military Reservation	5.5

Table 19.6 Australian model, Scenario A1b

Installation	Australian Scenario A1b, Prcp 20–99 change (in mm/day)
Hunter-Liggett Military Reservation	10.6
Camp Parks Military Reservation	8.5
Presidio of Monterey	7.9
Los Alamitos Armed Forces Reserve Center	7.6
Camp Roberts Military Reservation	7.5
Fort Polk Military Reservation	−7.4
Fort MacArthur	6.6
Redstone Arsenal	−5.6
Sharpe General Depot (Field Annex)	4.7
Anniston Army Depot	−4.6

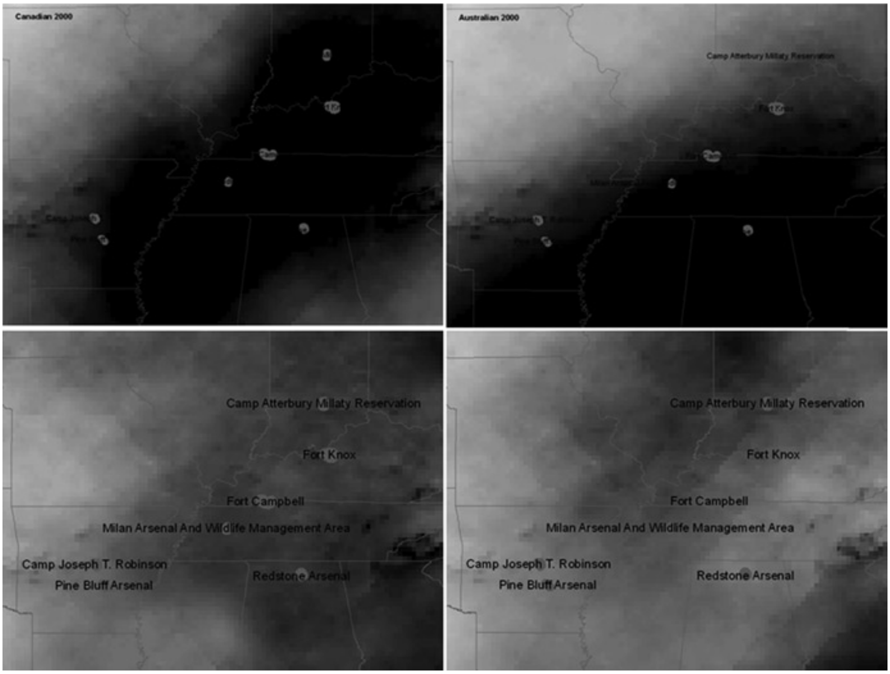

Fig. 19.9 Comparison on precipitation models in the central Mississippi-Ohio River valleys for 2000 and 2099. Darker means more rain. The Canadian Model (*right*) predicts more rainfall in 2099 than the Australian model (*bottom left*), although the amount decreasing between 2000 and 2099 in the Canadian Model is greater

Those installations showing the greatest decrease in predicted precipitation were mapped with the corresponding data from the Canadian and Australian models in Fig. 19.9. Both models agree that this region will become drier and that that end-point is roughly equivalent.

Since there appeared a consistency in those locations showing the greatest increase in predicted precipitation in Table 19.6 and in Sect. 6.2.2, we mapped those installations within the corresponding data from the Canadian and Australian models in Fig. 19.10. All of those installations are located along the mid to southern California coastline.

19.6.2 Temperature

Table 19.7 lists those installations that experience the greatest change In the *Globalized rapid economic growth* scenario for the Canadian Model (Scenario A1b).

All of the changes indicate a large decrease in expected temperature. This is why the research area is termed climatic change; the term “global warming” can be misleading.

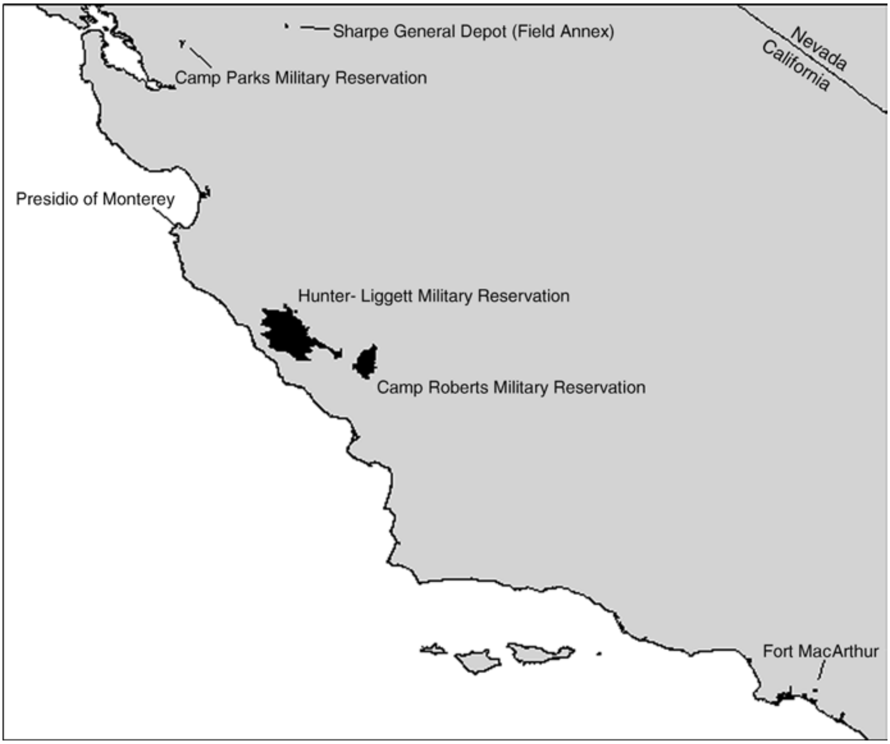

Fig. 19.10 Installations consistently showing the greatest increased precipitation

Table 19.7 Canadian model (Scenario A1b), installations that experience the greatest change in temperature

Installation name	Canadian Scenerio A1b, Temp 20–99 change°C
Fort Rucker Military Reservation	–9.6
Fort Benning Military Reservation	–9.3
Fort Bragg Military Reservation	–8.9
Fort Gillem Heliport	–8.9
Fort Stewart	–8.9
Fort McPherson	–8.8
Camp MacKall Military Reservation	–8.8
Hunter Army Airfield	–8.8
Fort Gordon	–8.8
Anniston Army Depot	–8.6

The group listed in Table 19.7 does not range across the country; rather there is a clustering of installations in the southeastern U.S. that include some of the Army's most important training and readiness installations (Fig. 19.11). Further, these

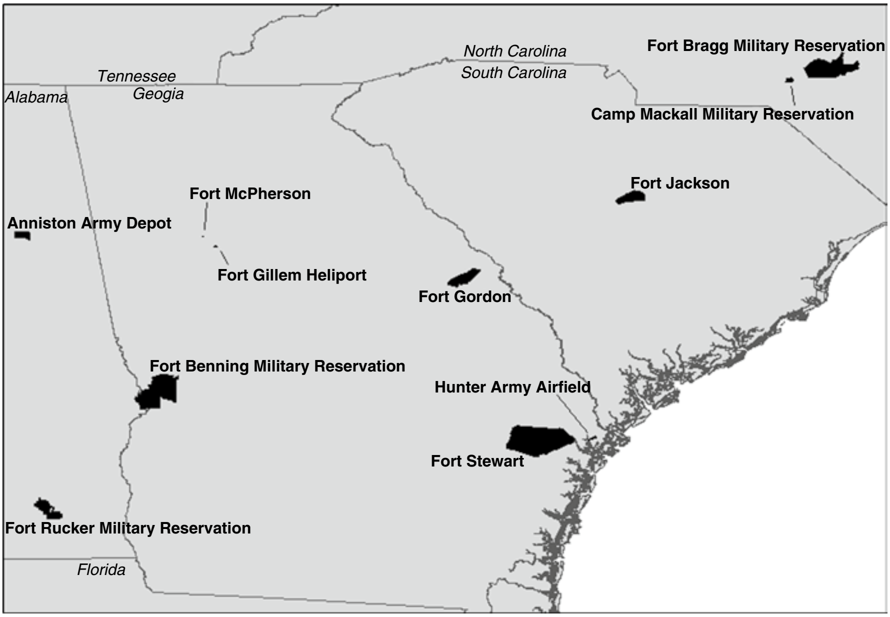

Fig. 19.11 In the *Globalized rapid economic growth* scenario for the Canadian model, the installations with the greatest change, a decrease in temperature, all cluster in the southeastern US

installations are concentrated in only three states: Alabama, Georgia, and North Carolina.

The Army installations that experience the greatest change under a sustainability scenario for the Canadian Model, Scenario B1, show no such spatial clustering (Table 19.8).

In fact, the increased temperatures seen with the installations listed in Table 19.8 are almost in reverse degree to the decreased temperatures seen in the Canadian A1 model above (Table 19.7). These installations reside first in the Montana/Utah area and second (with the exception of Buckley Air National Guard AFB) in or near Texas (Fig. 19.12). Though Texas and Oklahoma are not the worst impacted, their resident installations tend to be large and important military bases. In general then, the plains areas will become even warmer than they are now. Military personnel will need more protection from the heat and vehicles will experience greater stress.

In this scenario, what happened to the cooler southeastern installations? Table 19.9 lists Canadian Scenario B1 data for same installations listed in Table 19.7, for comparison.

The southeastern installations still indicate temperature decreases, but the decrease is not as great as at the warmer installations. In fact, Fort Bragg shows the greatest temperature decrease of any installation in the Canadian B1 scenario. The point here is that under the sustainability scenario, the greatest impacts to

Table 19.8 Army installations that experience the greatest change under Canadian model, Scenario B1

Installation	Canadian Scenario B1, Temp 20–99 °C change
Fort William H. Harrison Military Reservation	9.3
Fort Wolters	9.0
Fort Sill Military Reservation	9.0
Bearmouth National Guard Training Area	8.3
Fort Hood	8.3
Camp Swift National Guard Facility	7.7
Buckley Air National Guard Air Force Base (AFB)	7.6
Tooele Army Depot	7.3
Camp Bullis	7.3
Camp Williams	7.3

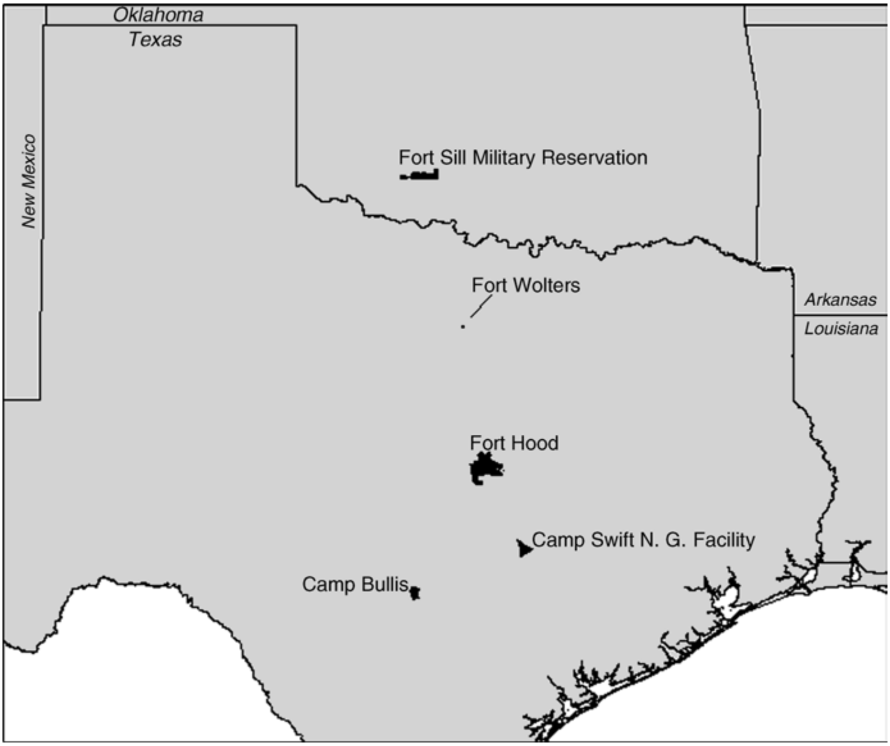

Fig. 19.12 Warmer Texas-area installations

temperatures will be in those areas experiencing increased temperatures. In other areas, temperatures will still decrease.

Table 19.10 lists those installations that experience the greatest change under the Australian A1b *Rapid Growth* scenario.

Table 19.9 Canadian model, Scenario B1, cooler installations

Installation	Canadian Scenario B1, Temp 20–99 change (in °C)
Fort Rucker Military Reservation	–5.7
Fort Benning Military Reservation	–5.1
Fort Bragg Military Reservation	–6.1
Fort Gillem Heliport	–4.7
Fort Stewart	–5.3
Fort McPherson	–4.6
Camp MacKall Military Reservation	–6.0
Hunter Army Airfield	–5.2
Fort Gordon	–4.9
Anniston Army Depot	–4.4

Table 19.10 Installations with the greatest temperature change under the Australian A1b

Installation	Australian Scenario A1b, Temp 20–99 change (in °C)
White Sands Missile Range	6.4
Fort Bliss	6.2
Fort Bliss McGregor Range	6.1
Fort Wolters	6.0
Fort Hood	5.8
Camp Bullis	5.7
Fort Carson Military Reservation	5.6
Camp Swift National Guard Facility	5.6
Buckley Air National Guard AFB	5.4
Natick Laboratories Military Reservation	5.4

Once again all of these locations show a temperature increase, though not as great as in the Canadian Model. This list largely overlaps the Canadian Model B1 list (Table 19.9) and includes installations slightly to the west of the previous top 10. Yet again as for precipitation, the Canadian B1 and the Australian A1 scenarios show greater impacts in the western U.S. In addition, the greatest change includes the same western region as shown in Fig. 19.12, with the addition of a group of members to the north.

19.6.3 Ecosystem Changes

Using the Bailey's ecosystem characterizations as shown in Figs. 19.5 and 19.6 based on the Canadian Model, Scenario A1b, *Globalized Rapid Economic Growth*, we derived an evaluation of those installations that will change by at least one ecosystem. Of the 128 installations investigated, fully 96 (or 75%) changed from the ecosystem they started with in the year 2000. Figure 19.13 shows an example

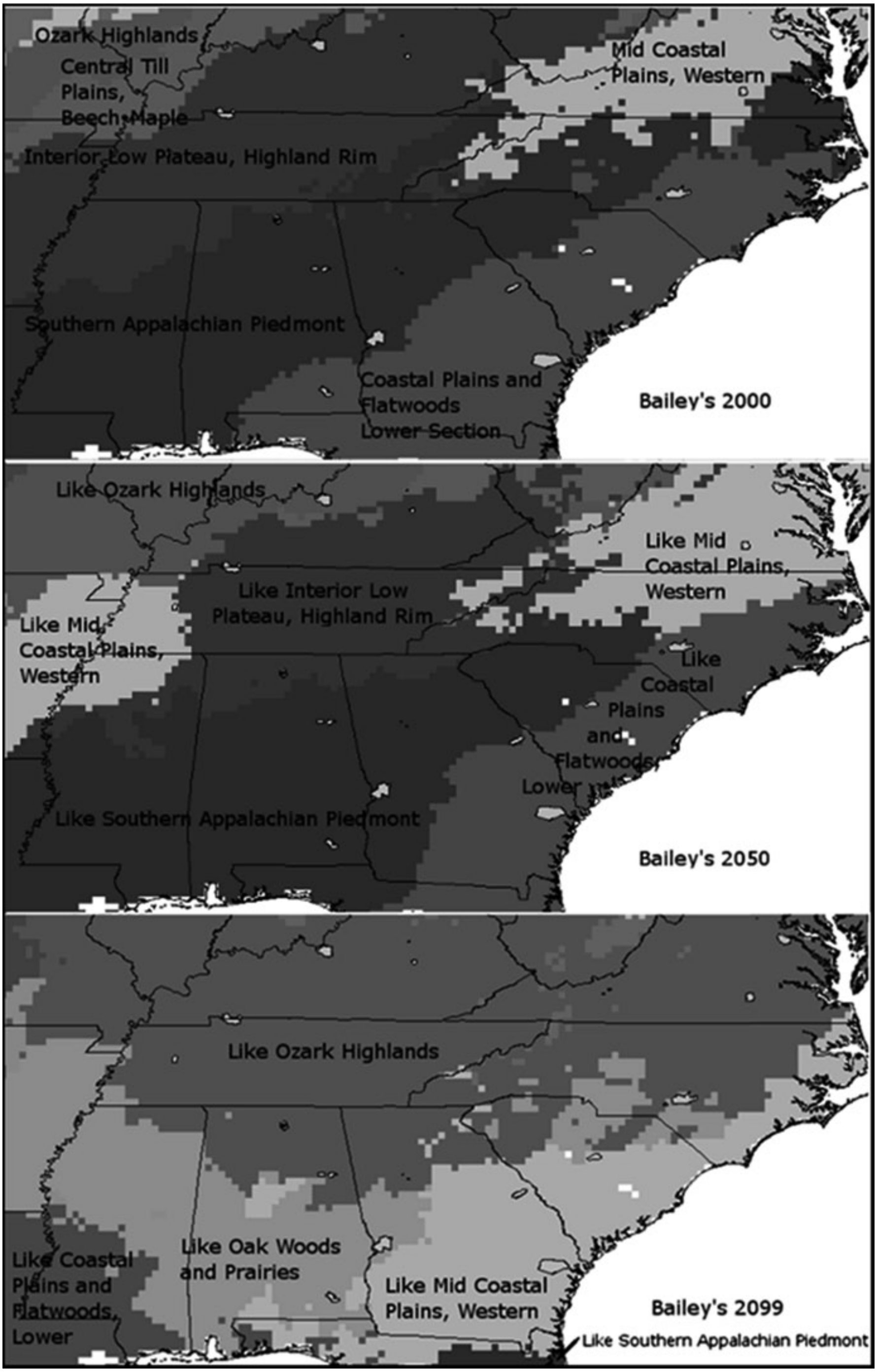

Fig. 19.13 Change in "Predictive" version of Bailey's ecosystems in the southeastern states. A strong migration in the southern direction is evident

of how ecosystems are expected to migrate in the years 2000, 2050, and 2099. The bottom line here is that installations are more likely than not to experience a major change.

If we instead apply the Canadian Model, Scenario A1b, *Globalized Rapid Economic Growth*, to Omernik's ecosystems using a similar analysis, we find that 102 of the 128 installations studied (or nearly 80%) of the installations ecosystems changed type. Once more, change in the natural landscape is vastly more likely than stability during the next 100 years.

Since there is a time lag between temperature and precipitation changes and responses in the ecosystem it needs to be clearly stated that these changes will slowly follow behind climate changes. Installation land managers can expect a continuously changing landscape in both the near future and the long-term horizon. Managing for preservation simply will not be an option in the future. This therefore implies that issues dealing with TES and invasive species will become increasingly problematic. Whole new areas of land management research must emerge to determine how the Army/DoD will change its management plans and how it will have to modify its current agreements with other agencies (e.g., Forest Service and Fish and Wildlife Service) based on climate change dynamics (Fig. 19.14).

We also rank-ordered climatic impacts on Army installations using the ecosystem changes based on the Hargrove ecosystem units. Table 19.11 lists the numerical degree of ecosystem change for the most affected installations.

These installations are distributed across the U.S. (see Fig. 19.15), but their names are familiar to us from the other analyses above. Only Warrenton Training Center and Sunflower Army Ammunition Plant are new installations appearing in this analysis for the first time.

For the entire analysis of 133 Army installations using the Hargrove/GAP method, at best 42 (32%) changed by less than 50% (under the PCM scenarios), but fully 132 (99%) changed by more than 50% (under the Hadley scenarios). Thus the Hargrove/GAP analysis finds an average of 65% in the most changed ecosystem category. Once again, ecosystem change is still much more likely than not.

As an example of how the results can be interpreted, we present predicted changes and the character of those changes at Fort Stewart, Georgia, according to both the PMC and Hadley models (Fig. 19.16). The region is shown with the installation outlined in red. Fort Stewart currently resides almost completely within the GAP ecoregion called Evergreen Plantations or Managed Pine. The configuration of the currently existing nearby ecoregions is shown in the upper right insert of Fig. 19.16. Compare that current situation insert with the predictions for the year 2050 (second row of inserts) for the PCM model, scenarios B1 and A1 and the Hadley model, and scenarios B1 and A1 respectively. Little of the landscape changes at Fort Stewart by the year 2050. Next, compare the current situation insert with the predictions for the year 2100 (third row of inserts) for the PCM model, scenarios B1 and A1 and the Hadley model, and scenarios B1 and A1, respectively. The PCM models suggest that Fort Stewart will be little changed. The Hadley

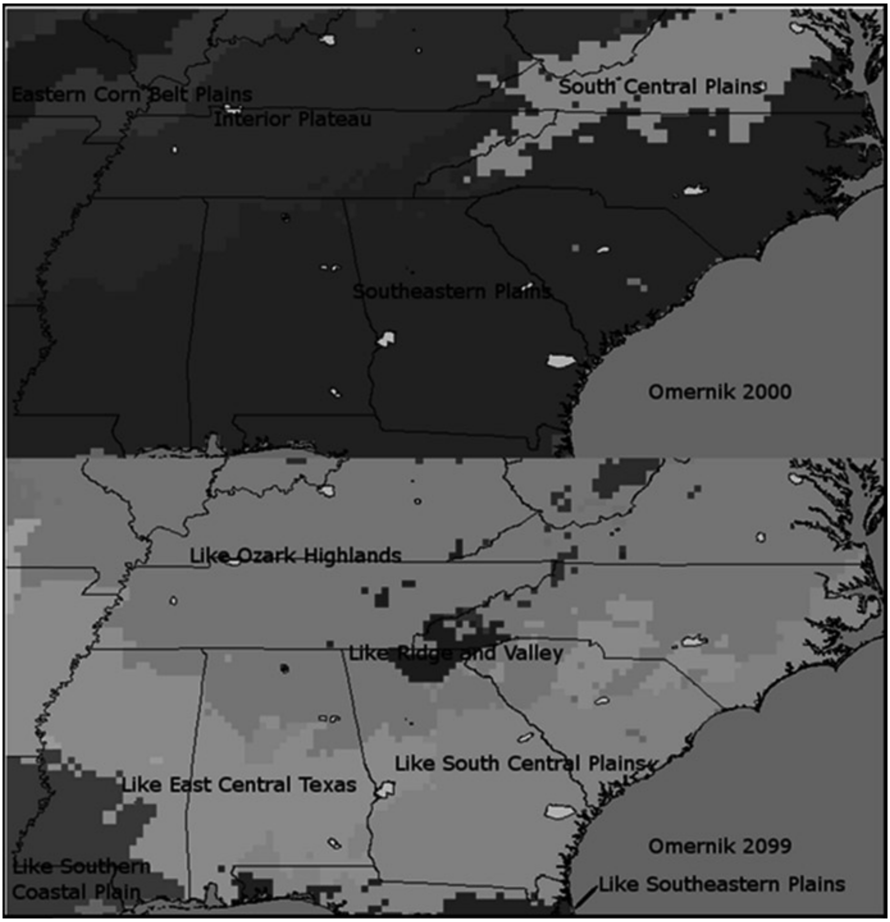

Fig. 19.14 Migration of Omernik's ecosystems in the Southeast U.S. from 2000 (*top*) to 2099 (*bottom*). The same gray scale is used for both images

model under the "sustainability" scenario shows little change in the Evergreen Plantations or Managed Pine distribution at Fort Stewart. However, the *Globalized Rapid Economic Growth* scenario shows that the Evergreen Plantations type will retreat and remain only in the river valleys. Fort Stewart will be completely covered by an ecosystem type without a current analogue. The land managers at Fort Stewart in this scenario will be dealing with land management questions and issues for which there is currently no similar landscape. There will be no example region from which they can take lessons or follow examples. They will be managing their installation without historic guidance. This will obviously be an entirely unprecedented land management problem.

Similar analyses maps are available for all CONUS military installations [8].

Table 19.11 Percent of installation area that changes to a new ecosystem by 2099, top ten installations

		80–100% Unchanged		50–80% Unchanged		0–50% Unchanged			
Percent habitat unchanged by climate change		PCM model				Hadley model			
Installation	Size (0.02 by 0.02) degree cells	PCMB1 2050	PCM B1 2100	PCM A1 2050	PCM A1 2100	HAD B1 2050	HAD B1 2100	HAD A1 2050	HAD A1 2100
Fort Lee Military Reservation	66	36	50	50	27	50	0	0	0
Warrenton Training Center Military Reservation	130	47	25	64	18	31	18	22	0
Umatilla Chemical Depot (Closed)	88	59	55	27	23	24	20	24	0
Anniston Army Depot	90	70	53	70	20	11	11	11	0
Sunflower Army Ammunition Plant	35	83	83	83	0	0	0	0	0
Fort Bliss McGregor Range	11190	35	31	29	35	43	44	23	12
Pine Bluff Arsenal	288	89	83	87	3	0	0	0	0
Fort Sill Military Reservation	900	42	38	38	38	38	38	38	0
Fort Campbell	925	96	74	82	4	19	0	1	0
Fort Gordon	792	78	64	80	12	19	13	13	0

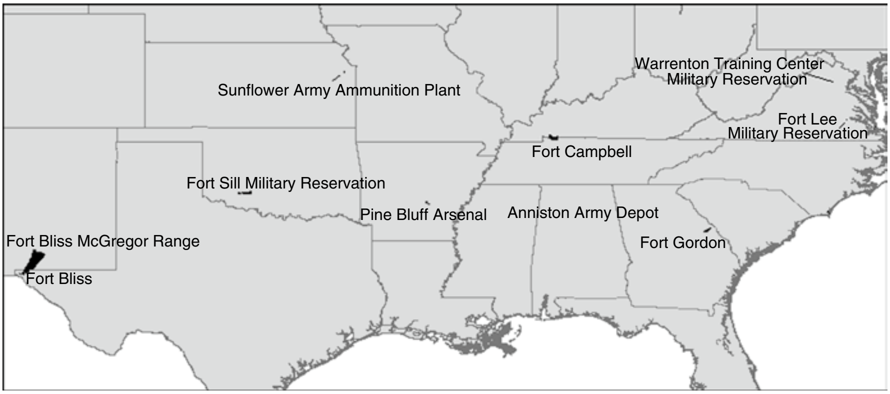

Fig. 19.15 Installations showing the greatest ecological change based on the Hargove MGC data. (Umitilla Chemical Depot in the northwest is not shown)

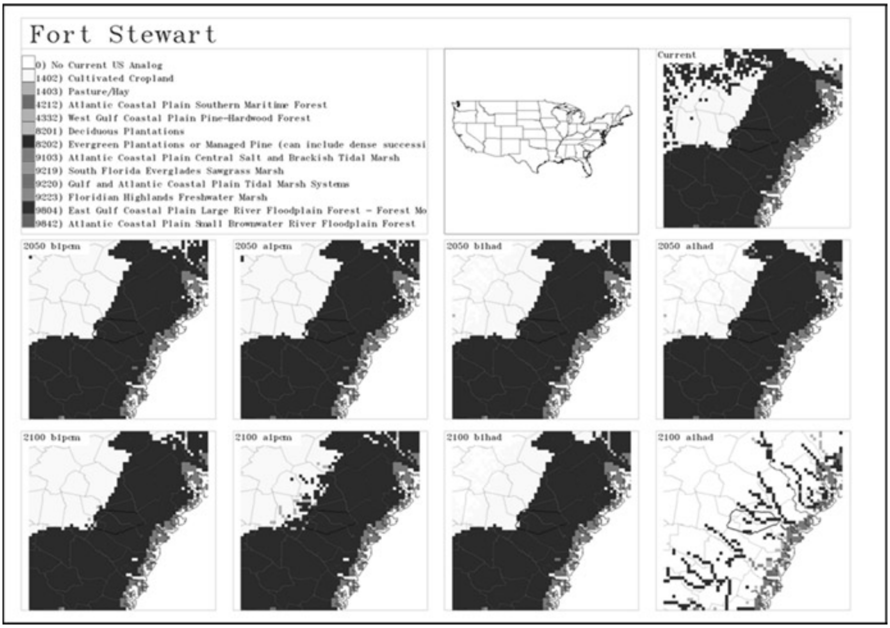

Fig. 19.16 More detailed analysis at Fort Stewart

19.6.4 *Climatic Change Effects on Erosion*

Potential erosion results are divided into two categories: high K-factor and low K-factor. The differences are relatively minor as both the high K-factor analysis and the low K-factor analysis tell the same basic story.

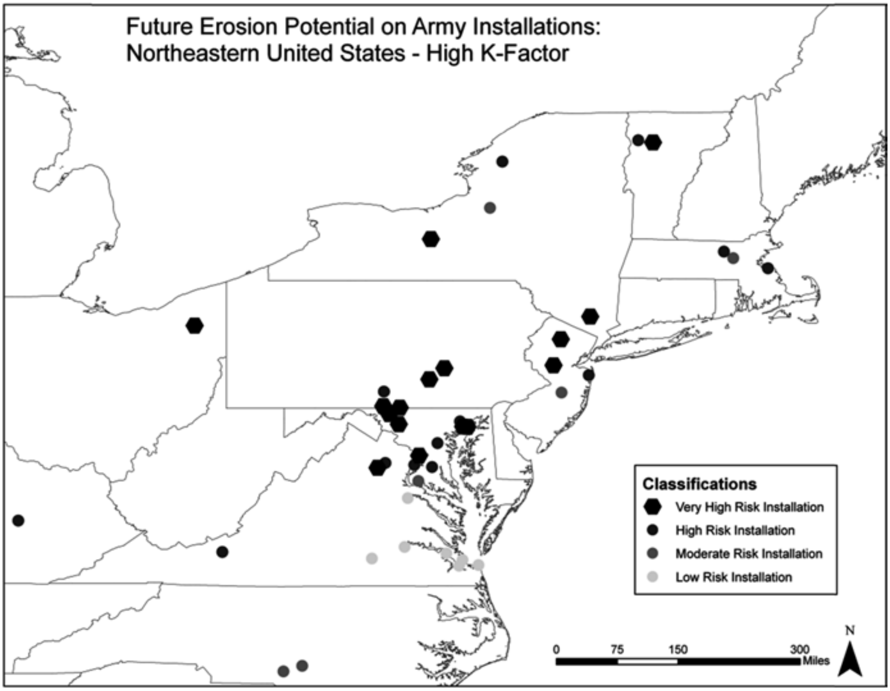

Fig. 19.17 Clustering of installations at higher risk for increased erosion in the eastern mid-Atlantic region

In the CONUS, there are two noticeable clusters of Very High Risk installations: the northeast and the northwest (Fig. 19.17). These clusters appear in both the high and low K-factor analysis with only slight variability. Those key installations that ranked in either the High or Very High risk of Erosion due to climate change in 2099 are shown in Table 19.12.

In multiple instances, the risk classification is different between the low K-factor and high K-factor analyses. This was expected and was the reason that we decided to include the results from both. However, even when the potential erosion risk does change, it never shifts more than one class in either direction.

Of the Very High Risk installations, Camp Atterbury and Aberdeen Proving Ground have particularly erodible soils, while Fort Knox has higher slope due to its proximity to the Ohio and Salt rivers. Yakima Firing Range is located near the eastern foothills of the Cascade Mountains and consequently has very high slope.

19.6.5 Analysis of Climatic Change Effects on TES

Since the projection of individual TES habitat changes is well beyond the scope of this preliminary review, this section will rely on making observations of what the

Table 19.12 Key installations that ranked in either the high or very high risk of erosion due to climate change in 2099

Key installations	Ranking: Low K-factor	Ranking: High K-factor
Aberdeen Proving Ground Military Reservation	Very high risk	Very high risk
Fort Knox	Very high risk	Very high risk
Yakima Firing Center	Very high risk	Very high risk
Camp Atterbury Military Reservation	High risk	Very high risk
Camp Riley Military Reservation	High risk	Moderate risk
Fort Campbell	High risk	High risk
Fort Dix Military Reservation	High risk	Moderate risk
Fort Drum	High risk	High risk
Fort Leonard Wood Military Reservation	High risk	High risk
Fort Polk Military Reservation (Pelham Range)	High risk	High risk
Fort Carson Military Reservation (Pinyon Canyon)	Moderate risk	Moderate risk
Fort Hood	Moderate risk	Moderate risk
Fort Leavenworth Military Reservation	Moderate risk	Moderate risk
Fort Pickett Military Reservation (Closed)	Moderate risk	Low risk
Fort Polk Military Reservation	Moderate risk	Low risk
Fort Riley Military Reservation	Moderate risk	Low risk
Fort Benning Military Reservation	Low risk	Low risk
Fort Bliss	Low risk	Low risk
Fort Bliss (McGregor Range)	Low risk	Low risk
Fort Bragg Military Reservation	Low risk	Moderate risk
Fort Carson Military Reservation	Low risk	Low risk
Fort Gordon	Low risk	Low risk
Fort Irwin	Low risk	Moderate risk
Fort Jackson	Low risk	Low risk
Fort Stewart	Low risk	Low risk
White Sands Missile Range	Low risk	Low risk
Yuma Proving Ground	Low risk	Low risk

Legend:
(darkest shading) = "Very high risk"
(dark shading) = "High risk"
(light shading) = "Moderate risk"
(lightest shading) = "Low risk"

preceding climatic changes imply for TES at military installations. We suggest that this is the beginning of the groundwork for more detailed and in-depth studies relating to climatic change impacts on TES.

The Bailey's and Omernik's ecosystem migration results indicate that well over three quarters of CONUS Army installations are likely to change ecosystems due to climate change. The Hargrove/GAP-based results show roughly 65% of the installations are in the Red: 50% or greater change in ecosystem category. So the evidence is overwhelming that there will be major changes. Since any species depends on its current community composition for habitat and survival resources, the change of an entire ecosystem will have many implications for species survival. General consequences that can reliably be based on these types of considerations include:

- The likelihood of currently identified TES surviving will be greatly decreased no matter how much money or time is expended. Their local habitat is likely to have moved or disappeared altogether.
- As pockets of habitat locally shrink, many new TES will emerge.
- As ecosystems shift, some species will dramatically gain habitat, but NOT LOCALLY.
- Locally, large numbers of species will be more challenged for access to traditional resources. Therefore, locally, the number of new TES candidates will increase dramatically if not overwhelmingly.
- The Army's current policy of managing for preservation simply will not be an option.
- New ecosystems not currently in existence will emerge on Army lands; therefore:
  - The Army/DoD will have to modify its current agreements with other agencies based on climate change dynamics.
  - The cost to manage TES (as well as Army lands in general) will greatly increase and there is no reason to believe it will cease rising since the ecosystems will not stop migrating at the end of our available projections in 2099.
  - Whole new areas of land management research will emerge dealing with how the Army/DoD will change its TES management plans (as well as many other management plans).

19.6.6 Analysis of Climatic Change Effects on Invasive Species

As with the issue of TES, this section will rely on making observations of what the preceding climatic changes imply for invasive species at military installations.

Many of the basic observations mentioned for TES also apply to the concern of invasive species. Here we enumerate additional concerns. The most important single observation is that ecosystems will change at most installations. Unlike TES, however:

- As ecosystems shift, some species will dramatically gain habitat.
- Invasives from similar ecosystems are likely to become established because global travel is so easy now.
- Consequently, treating invasives in a traditional manner will be very difficult.
- Financial and labor resources to deal with invasives will be strained if not broken.

The entire disciplinary subject has to change dramatically at its core. Since the basis for the current situation will change, we will be challenged to redefine the concept of invasives. For example, in the new ecosystem, will the residual old community members be called TES, or are they now to be known as invasive species? Obviously such a fundamental question will require an entirely new research.

19.7 Summary and Recommendations

19.7.1 Summary

As with other agencies, the effects of climate change are expected to impact CONUS military installations. Climate change has the potential to affect these major concerns at most CONUS installations:

- Precipitation amounts
- Temperature values
- Ecosystem type and or traits
- Erosional characteristics
- The management of TES
- The appearance and increase of noxious invasive species

The purpose of this work was to conduct a preliminary evaluation using basic data and easily available information to provide initial insight into these questions, issues, and concerns in a scientific manner.

19.7.1.1 Precipitation

- The amount of precipitation change at Army installations will range from −9 to + 10.6 mm/day.
- Mostly highly changed installations tend to clump into specific regions.
- Installations in the southeast will experience the greatest drying trend.
- Installations along the mid to southern California coast will experience the greatest increase in rainfall.
- Installations that regularly appear highly impacted under different models and different model scenarios are:
    - For drying conditions:
        - Fort Campbell
        - Fort Knox
        - Milan Arsenal and Wildlife Management Area
        - Camp Atterbury Military Reservation
        - Redstone Arsenal
        - Pine Bluff Arsenal

- For increasingly wet conditions:
  - Hunter-Liggett Military Reservation
  - Presidio of Monterey
  - Camp Roberts Military Reservation

19.7.1.2 Temperature

- The amount of temperature change at Army installations will range from −9.6 to +9.3°C/month.
- Mostly highly changed installations tend to clump into specific regions.
- Installations in the southeast will experience the greatest decrease in temperatures.
- Installations in the Texas, New Mexico, and Colorado regions will experience the greatest increase in temperatures.
- Installations that regularly appear highly impacted under different models and different model scenarios are:
  - For decreasing temperature conditions (less drastic in the Australian Model):
    - Fort Rucker Military Reservation
    - Fort Benning Military Reservation
    - Fort Bragg Military Reservation
    - Fort Gillem Heliport
    - Fort Stewart
    - Fort McPherson
    - Camp MacKall Military Reservation
    - Hunter Army Airfield
    - Fort Gordon
    - Anniston Army Depot
  - For increasing temperature conditions:
    - Fort Wolters
    - Fort Hood
    - Camp Swift National Guard Facility
    - Buckley Air National Guard AFB
    - Camp Bullis

19.7.1.3 Ecosystems

Ecosystem change predictions were modeled under three different ecosystem definitions (Bailey's, Omernik's, and the USGS 2010 GAP analysis), under three different climatic models using two different scenarios of the direction of future growth. In all cases:

- Changes will occur all across CONUS, and changes will often be major changes (as measured by percent of ecosystem on an installation unchanged by 2099).

- Since there is a time lag between temperature and precipitation changes and responses in the ecosystem, ecosystem shifts will slowly follow behind climate changes.
- The percent of Army installations that will change from their current ecosystem to a new one ranged from a low of 65% to a high of 80%. Thus a different ecosystem by 2099 will be the normal situation for Army land managers.
- Changes will often be to new ecosystems that do not currently exist; therefore, there will exist no current ecosystem after which installation land managers will be able to model their management activities.
- The mostly highly changed ecosystems will be at:
  - Fort Lee Military Reservation
  - Warrenton Training Center Military Reservation
  - Umatilla Chemical Depot (Closed)
  - Anniston Army Depot
  - Sunflower Army Ammunition Plant
  - Fort Bliss McGregor Range
  - Pine Bluff Arsenal
  - Fort Sill Military Reservation
  - Fort Campbell
  - Fort Gordon

19.7.1.4 Erosion

Erosion increases dramatically as rainfall events increase in intensity. Our research found that, as rainfall increases in amount, intensity can also be expected to increase. Thus in areas predicted to increase in precipitation to the year 2099, we can expect greater erosion problems. We used nationwide data for three factors: slope, soils, and projected precipitation intensity due to climate change (a coalescing of six different climate models) to model erosion impacts to 2099. We found that the key installations that ranked in either the High or Very High risk of erosion due to climate change in 2099 include:

- Aberdeen Proving Ground Military Reservation
- Fort Knox
- Yakima Firing Center
- Camp Atterbury Military Reservation
- Camp Riley Military Reservation
- Fort Campbell
- Fort Dix Military Reservation
- Fort Drum
- Fort Leonard Wood Military Reservation
- Fort Polk Military Reservation (Pelham Range)

19.7.1.5 TES

- The likelihood of currently identified TES surviving will be greatly decreased no matter how much money or time is expended. Their local habitat is likely to have moved or disappeared altogether.
- As pockets of habitat locally shrink, many new TES will emerge.
- As ecosystems shift, some species will dramatically gain habitat, but NOT LOCALLY.
- Locally, large numbers of species will be more challenged for access to traditional resources. Therefore, locally the number of new TES candidates will increase dramatically if not overwhelmingly.
- Managing for preservation simply will not be an option.
- New ecosystems not currently in existence will therefore emerge on Army lands.
- Whole new areas of land management research will emerge dealing with how the Army/DoD will change its TES management plans (as well as many other management plans).
- The Army/DoD will have to modify its current agreements with other agencies based on climate change dynamics.
- The cost to manage TES (as well as Army lands in general) will greatly increase and there is no reason to believe it will not continue to rise since the ecosystems will not stop migrating at the end of our available projections in 2099.

19.7.1.6 Invasive Species

Many of the conclusions for the TES analysis apply to noxious invasive species as well. In addition:

- As ecosystems shift, some species will dramatically gain habitat.
- Invasives will become more common no matter how they are defined.
- Invasives from similar ecosystems are likely to become established because global travel is so easy now. Invasives will be derived from sources that are:
  - Near local sources that are migrating to keep up with the changing climate. (That is, they represent the new ecosystem—so are they really invasives?)
  - Exotic sources from distant regions. As is the case now, species will use transportation (shipping and air travel in particular) to invade new habitats. If the volume of transportation increases, so will the number of exotic invasives.
- Thus, treating invasives in a traditional manner will be very difficult.
- Financial and labor resources to deal with invasives will be strained if not broken.

19.7.1.7 Installations at Greatest Risk Due to Climate Change

It is apparent from the lists presented in the precipitation, temperature, ecosystem, and erosion analyses above that certain installations appear multiple times for high probability of modification by 2099 due to climate change. Since this chapter was developed based on the research of three independent investigations by three independent researchers using many different climate model predictions and several different scenarios, there can be little question that when these Army installations appear repeatedly, the best available data indicates that the changes will be real and dramatic. All three research efforts that supported this work examined well over 100 installations, but the lists provided in this chapter included only the top 10 changed installations; i.e., less than 8% of all the locations evaluated. Consequently, when an installation appears multiple times in multiple lists, significant changes are highly likely; for example:

- Fort Campbell appears in three lists.
- Fort Knox appears in two lists.
- Camp Atterbury Military Reservation appears in two lists.
- Pine Bluff Arsenal appears in two lists.
- Fort Gordon appears in two lists.
- Anniston Army Depot appears in two lists.

Figure 19.18 shows the distribution of these Army installations.

After so many variations in analyses, it is significant that these six installations are distributed over such a small section of the U.S. Certainly other installations not on this list but in the region (named in Fig. 19.18 in blue) are likely to share the fate and problems that these six will experience.

An installation not included in this list will not escape climatic change. As mentioned above, anywhere from 65% to 80% of the installations are expected to experience change from their current ecosystem identification. That is no small matter. It implies many subordinate changes in the character and species that reside in those locations. Throughout this chapter, and particularly in this section, we have highlighted the greatest changes; however, military land managers can expect climate change challenges almost anywhere in CONUS.

19.7.2 Recommendations

19.7.2.1 For Army Trainers

Climate change implies that installation missions may have to change. For example, if your primary “tropical” training installation is likely to become much drier, you are likely to look elsewhere for an appropriate training facility. As climate changes, the supplies required to support your field personnel will have to change too. In a hotter climate, for example, you will require more drinking water. But where are you going to get it if the local supply is limited?

If erosion increases on a tracked vehicle training facility (as would have been the case for the old mission at Fort Knox, a multi-impacted location), can it sustain the training exercises it was established to support?

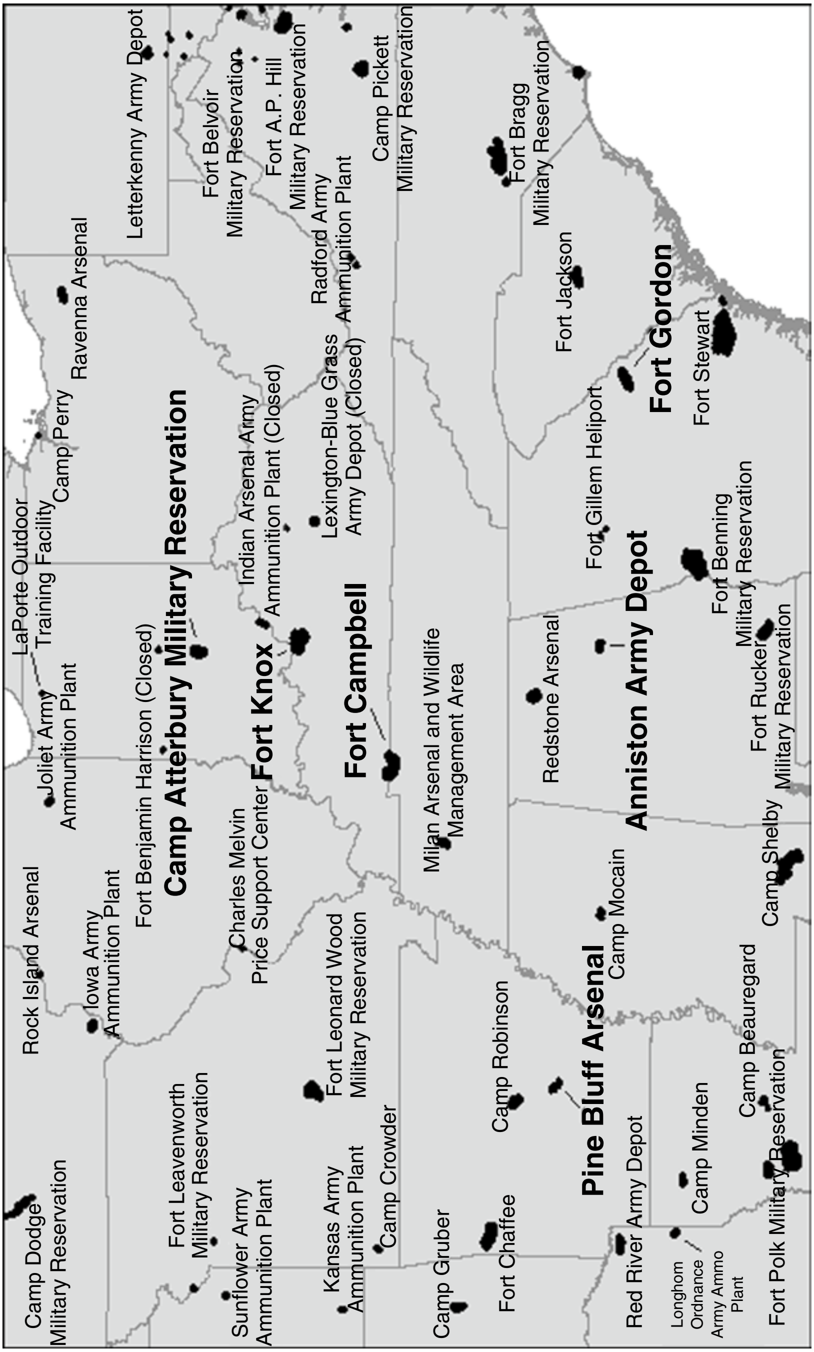

Fig. 19.18 Installations most often highly impacted by climatic change concerns from multiple sources (*bold black font*) and others in the same region (*smaller font*)

The implications of climate change need to be investigated in relation to installation missions at the DoD, Army, and Regional levels.

19.7.2.2 For Army Land Managers

One may consider climate change and even the resulting ecosystem change as "symptoms." This report does not address the root causes of climate change. Rather, it focuses on its effects and the possible implications of those effects on the operation of Army installations in the CONUS.

What installation land managers can expect in the near future and over the long term is a continuously changing landscape. Managing for preservation simply will not be an option. This therefore implies that issues dealing with TES and invasive species will not only persist, but will worsen. Costs to manage Army lands in the traditional manner will skyrocket. New ecosystems will emerge for which no current analogue or model exists. Traditional land management techniques will no longer work. So a new area of land management research must emerge to determine how the Army/DoD will change its management plans and how it will have to modify its current agreements with other agencies (e.g., Forest Service and Fish and Wildlife Service) based on climate change dynamics.

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Part IV
Coastal Applications

Chapter 20
Adaptation in Coastal Systems

Vulnerability and Uncertainty Within Complex Socioecological Systems

G.A. Kiker, R. Muñoz-Carpena, N. Ranger, M. Kiker, and I. Linkov

Abstract The vulnerability of coastal regions to adverse climatic and environmental drivers is well understood and has been demonstrated by several recent events, such as Hurricane Katrina, the oil spill along the U.S. Gulf Coast, and Cyclone Nargis in Myanmar. Trends including climate change, degradation of coastal ecosystems, population growth, and aging infrastructure are likely to increase vulnerabilities in the future. While there may be broad acceptance for including limited climate change-related options within current planning methodologies, new types of tools, policies, and decision-making approaches may be required that move beyond the mainstream processes to reduce risks while addressing the complex nature of these social/biological/physical systems. In particular, adaptation demands a fundamentally different decision regime than the current, historically focused methods. The objective of this chapter is to provide an introduction and conceptual overview to

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the section on adaptation to climate change within coastal systems. As a result of coastal group discussions in the 2010 NATO-Iceland meeting, we highlight four main points concerning adaptation to climate change in coastal areas:

1. Coasts have a set of layered vulnerabilities that contribute to current and future risks.
2. People matter in the adaptation process and should be included at multiple stages in the decision process.
3. Governance also plays a fundamental role in the adaptation process.
4. There are challenges to decision making in adaptation, but there are also a range of powerful concepts, tools, and case studies available to aid decision makers.

Within these sections, we highlight theories regarding adaptation within complex socioecological systems along with case studies to give examples of progressive analysis and planning for uncertain future events. The chapter concludes with a discussion of research and practice gaps for further consideration within the overall section.

20.1 Introduction

Coastal areas around the world already face increasing risks as a result of multiple parallel trends including rising sea levels, growing population, degraded coastal ecosystems, and aging and inadequate infrastructure [32]. Recent catastrophic events on the U.S. Gulf Coast due to adverse climatic and oil spill events have drawn attention to existing vulnerabilities. These demand more proactive responses than those historically employed: responses that integrate scientific, engineering, and social analyses and take account of uncertain present and future conditions. With respect to climate change, the National Research Council [62] reports that governmental agencies, private institutions, and individuals are "conceptually and practically unprepared" to either address the challenges or capitalize on the opportunities presented by uncertain events. In addition, the NRC report advises that the application of past climate information (and their associated probabilities of extreme events) are no longer valid for the design and implementation of infrastructure or societal policies such as zoning and transport. As such, climate change will create a "novel and dynamic decision environment" [62] that demands a fundamentally different decision regime than the current, historically focused methods.

While various institutional response efforts have been made in preparation for adverse circumstances, significant challenges remain in addressing pervasive management attitudes towards managing uncertain future events [60]. While traditional command-and-control philosophies have been historically useful in addressing localized, single-dimension hazards, they may confound or block systemic, multi-agency solutions to more complex environmental challenges. Uncertainty in estimations of climate change effects and potential impacts is a fundamental issue for decision making regarding potential adaptation responses in coastal areas.

Gunderson [28] describes two of the most common human mechanisms for mitigating uncertainty within complex environmental problems: (1) simply assume it away entirely, or (2) seek "spurious certitude"; that is:

> …to break a problem down into trivial questions spawning answers and policy actions that are unambiguously "correct," but, in the end, are either irrelevant or pathologic [28].

In terms of forming new legal instruments (i.e., policy, regulations) or a new governing institutions (e.g., committees) spurious certitude offers an alluring proposition for decision makers seeking certainty in the form of mechanisms under their control [28]. As an example of nonadaptive decision making in existing complex environmental challenges, Macey [51] presents a systematic review and critique of agency responses to uncertainties within large-scale, contaminated sites via the Superfund/CERCLA process. In many ways, these complex cleanup challenges mirror the socioenvironmental issues at play within coastal areas. Uncertainty within technical and social spheres can confound more adaptive approaches to integrating the diverse information inherent within complex environmental problems.

Thus, an overarching problem statement for the Coastal Adaptation working group was framed as follows: While much scientific effort has been expended towards the identification of coastal vulnerabilities to climate change, most adaptation policies or plans focus on easily understood, single-issue concerns that require little change in terms of existing institutions and governance mechanisms. Solutions that address more adaptive decision making across complex, multidimensional social and biophysical issues that evolve over a long period of time are avoided because of the endemic uncertainty inherent within technical assessments, societal institutions, and human understanding. In some situations, the selection and promotion of simple, broadly acceptable solutions may be a sensible first step. Given that there appeared to be little opportunity for adaptation actions for climate change alone, Smit and Wandel [81] cited many examples to highlight the need for incorporating climate adaptation options into other, more immediate, decision objectives. However, the authors caution that potential disadvantages exist where quickly implemented solutions may limit the content or consideration of potential alternatives, especially if current conditions change rapidly from previous forecasts.

Given these challenges, the objective of this chapter is to provide an introduction and conceptual overview to the section on adaptation to climate change within coastal systems. As a result of coastal group discussions in the 2010 NATO-Iceland meeting, we highlight four main points concerning adaptation to climate change in coastal areas:

1. Coasts have a set of layered vulnerabilities that contribute to current and future risks.
2. People matter in the adaptation process.
3. Governance also matters in the adaptation process.
4. There are challenges to decision making in adaptation, but there are also a range of powerful concepts, tools, and case studies available to aid decision makers in moving forward.

Accordingly, this chapter is divided into five sections:

1. A review of general vulnerability and uncertainty concepts
2. A more specific, coastal-focused review of risks and potential threats
3. A section that reviews the role of people and decision making within systematic and adaptive management
4. A governance section that highlights the fundamental role of governance for developing strategies for mitigating adverse effects
5. A tools section to highlight methods and frameworks for integrating complex sectors into adaptive decision making

20.2 Exploring Vulnerability and Uncertainty Assessment for Adaptive Responses: Theories and Review

This section provides a limited, conceptual overview of concepts and theories that underpin notions of vulnerability, adaptation, and integration between biophysical and sociocultural systems. It focuses on basic definitions of vulnerability and adaptive capacity with additional sections highlighting complex socioecological systems and systemic uncertainty.

20.2.1 Vulnerability and Adaptation

Smit and Wandel [81] provide a systematic review of adaptation with emphasis on vulnerability and adaptive capacity as key elements in human responses to climate variability and change. The vulnerability of a social or ecological system is often described as a function of exposure and sensitivity [39, 81]. As an expansion of the vulnerability concept, Turner et al. [85] provide a review of traditional vulnerability paradigms starting with the Risk-Hazard (RH) approach [15, 37], which mirrors traditional toxicological definitions to describe whether a phenomenon has some form of contact with organisms (exposure) and the concomitant effect or sensitivity displayed by that organism in reaction to the stimulus. Weaknesses in the RH approach such as the lack of feedbacks and societal/cultural impacts led to the evolution of a Pressure and Release (PAR) paradigm [12], which focused on conditions leading to exposure and vulnerability [85]. The PAR outlook focused more on social groups and their reaction to adverse events. Turner et al. [85] maintain that both RH and PAR frameworks do not focus enough on the coupled nature of social and environmental forces along with their concomitant feedbacks. The authors maintain that entitlement, coping, and resilience figure prominently in clearly articulating vulnerabilities within socioecological systems.

A social or ecological system's adaptive capacity is dynamic and responds to a range of environmental drivers with varying levels of success. Smit and Wandel [81] describe adaptive capacity in terms of a wide variety of factors ranging from social network stability to infrastructure robustness to ecological resilience with both local and regional determinants. The authors discuss a range of environmental factors that are within or at the edge of a "coping range" to describe the adaptive capacity a population to uncertain events. For example, while a coastal community may be fully resilient to a certain number of adverse storm events, changes in the storm frequency or intensity may push communities towards the edge of viability. Even regional or national policies such as the availability or cost of insurance may be critical to a population's adaptive capacity. Smit and Wandel [81] maintain that these various elements are nested in a hierarchical model of cultural and physical determinants occurring at both global and local scales.

In addition, given the differing content and scale of cultural and physical determinants, maladaptive options are possible given some decision scales. Maladaptation has been defined as:

> … an action or process that increases vulnerability to climate change-related hazards. Maladaptive actions and processes often include planned development policies and measures that deliver short-term gains or economic benefits but lead to exacerbated vulnerability in the medium to long term. [86].

An example of maladaptive options would be the adaptive response of upstream farmers along a river system to install irrigation systems to adjust for increasingly variable rainfall patterns. While this option may be prudent for their own viability, the subsequent increase in river extractions may result in significant problems downstream to other users and estuaries. Thus, vulnerability and adaptation responses at local scales may need to be balanced against larger societal and ecosystem goals in terms of coordinating responses of various sectors.

20.2.2 Uncertainty Within Complex Socioecological Systems

Uncertainty is an everpresent, yet often avoided aspect of human decision making. Bammer and Smithson [6] provide a comprehensive and multidisciplinary overview of uncertainty and its role within society ranging from hazard risk probabilities to religious perspectives to musical improvisation. Within the analysis of potential climatic changes and the exploration of potential adaptive responses, uncertainty can have direct effects as it is translated (either with or without statistical description) into subsequent model development and use. An important motivation of computational model development and multiscale simulation is the assumption that the information derived from these tools will allow managers and decision makers to better comprehend system dynamics and craft meaningful or appropriate solutions to adverse potential conditions. Unfortunately, integrated climate, hydrological, and ecological models are often complex and require a large number of uncertain inputs. Such mathematical and logical models are built in the presence of uncertainties of various types (e.g., input variability, model calibration data, and scale). In addition, there is a growing interest in evaluating the contribution of model structural uncertainty (i.e., from expert judgement, model algorithms, and code design) to the overall uncertainty of the model outputs in terms of spatial, temporal, and complexity levels [9, 11, 16, 23, 93]. The role of uncertainty analysis is to propagate all these uncertainties onto a model output, while sensitivity analysis determines the strength of the relation between a given uncertain input and a model output. Thus sensitivity analysis identifies the key contributors to uncertainties, while uncertainty analysis quantifies the overall uncertainty, so that together they contribute to a reliability assessment of the model [77]. If model uncertainty is not evaluated formally, the science and value of the model will be undermined [10].

The issue of uncertainty of model outputs has implications for policy, governance, and management, but the source and magnitude of uncertainty and its effect on socioecological assessment has not been studied comprehensively [10, 56, 80]. An important current issue and research objective within the analysis of uncertain, complex socioecological systems is the identification and prediction of critical transitions [75, 76]. Often complex systems show high resilience to external drivers until some tipping point at which the system rapidly changes to a new state. While the authors point to a set of generic yet critical features of a system that may give early indications of tipping points, research into these rapid transitions continues and large uncertainties remain.

20.3 Layered Vulnerabilities: Characteristics of Risk and Uncertainty Within Coastal Regions

Coastal regions are important centers of economic activity, human settlement, and ecosystems. Thirteen of the 20 most populous cities in the world are on coasts. Today, around 10% of the world's population lives within 10 m above sea level [52]. Coasts are areas of rapid population growth and significant infrastructure investment. They are also areas highly exposed to natural hazards, such as storms, flooding, and salt-water intrusion. Climate change will exacerbate existing pressures in these regions. Many coastal systems in NATO countries are heavily engineered to defend against these natural hazards, but in most cases this engineering does not account for climate change [66]. The combination of these factors means that there is an urgent requirement to begin adapting risk management infrastructure, policies, and processes to account for the long-term challenges.

Importantly, coastal areas are also valuable natural systems in their own right. As recent studies have pointed out [59], shorelines where natural systems are maintained (e.g., barrier islands and wetlands) often withstand coastal hazards with more success than highly altered areas. Thus there is a need to recognize the economic value of coastal processes in adaptation decision making

Table 20.1 Climate change-related drivers of risk in coastal regions [67]

Climate change impacts			Interacting factors	
			Climate	Non-climate
Sea level rise	Inundation	Elevated extreme water levels	Wave/storm climate, erosion, sediment supply	Sediment supply, flood management, erosion, land reclamation, land use
		Backwater effect from rivers	Runoff	Catchment management and land use
	Morphological change	Wetland loss (and change)	CO2 fertilization of biomass production, sediment supply, and migration space	Sediment supply, migration space, land reclamation (i.e., direct destruction)
		Erosion (of beaches and soft cliffs)	Sediment supply, wave/storm climate	Sediment supply
	Hydrological change	Saltwater intrusion (surface and groundwater)	Runoff/rainfall	Catchment/aquifer management (overuse), land use
		Rising water tables/impeded drainage	Runoff/rainfall	Land use, aquifer use, catchment management
Changes in storminess	Inundation	(as above)		
	Wind	Damage to buildings and infrastructure	n/a	Land use and building standards
	Rainfall	Local flooding	Runoff	Land use, catchment management, and building standards

20.3.1 Layers of Risk

Climate change is one of the most significant challenges we face, in terms of the potential scale of the impacts and the breadth and extent of the adjustments required to limit and reduce those impacts. Climate change will affect coastal regions in several ways: through increases in sea level; changes in storm characteristics (including tropical cyclone, winter storms, and storm surge); local hydrological changes (e.g., wetland loss and salt water intrusion); and ocean acidification and degradation of coastal ecosystems. These changes will impact the morphology of climate-related risks in coastal regions. Table 20.1 provides a summary of the key drivers of risks in coastal regions and the interacting climatic and non-climatic layers.

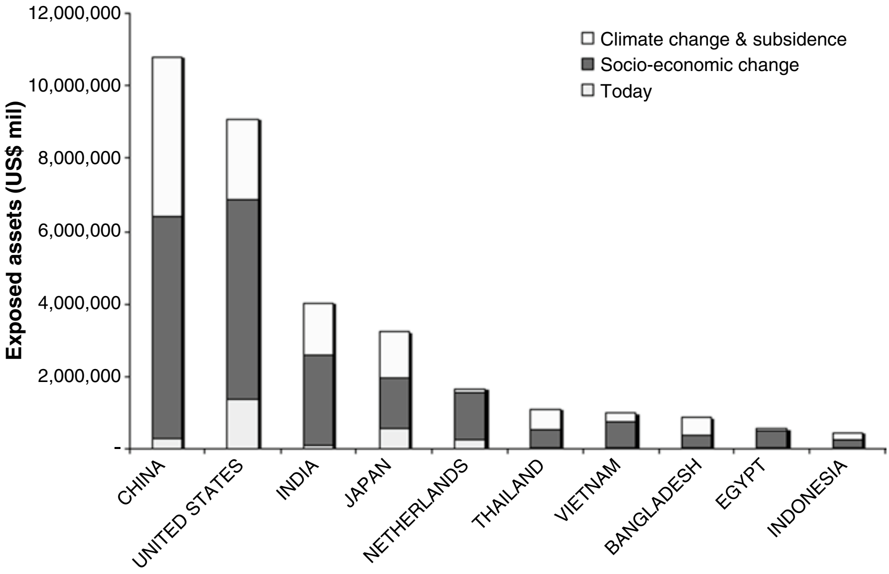

Fig. 20.1 Top 10 countries ranked by assets exposed to a 1-in-100-year storm surge today and in the 2070s, showing the relative contributions of socioeconomic change and climate change and subsidence [58]

Climate change is one of several drivers of change in coastal regions. In many regions, the largest driver of increasing risks over the next few decades will be socioeconomic trends; in particular, population and economic growth, urbanization, and migration to the coasts. Nicholls et al. [58] demonstrated that, globally, two-thirds of the increase in exposure to storm surge in port cities by 2070 is driven by these socioeconomic trends (Fig. 20.1). The other third is driven by sea level rise, changes in storminess, and—to a lesser extent—local subsidence. Together, Nicholls et al. [58] estimated that by the 2070s the number of people exposed to a 1-in-100-year storm surge in the world's most populous coastal cities will rise from 40 million people today to around 150 million. This exposure is highly concentrated in a handful of cities. In parallel, the exposure of assets to climate change is expected to rise from 6% of global GDP today to 9% by the 2070s. An increase in exposure does not necessarily represent increased risk, if it is accompanied by investments in protection and risk reduction. Given that it is impossible to eliminate all risk, Hallegatte et al. [92] note that property development behind flood walls can lead to increased residual risk, putting more people and value at risk if a large event occurs. The importance of the socioeconomic driver of increasing risk relative to climate change depends on the scale of those trends and investments in coastal protection.

Subsidence can also be an important driver of increasing risk in some areas. Natural subsidence is caused by tectonic movements and glacial-isostatic adjustment (i.e., the rebalancing of continents following the melting of ice sheets) and affects many regions, particularly deltaic cities (e.g., Tokyo, London, and New Orleans), and this will tend to aggravate increases in exposure due to sea level rise.

Table 20.2 Projections of global mean temperature increase and sea level rise from the IPCC fourth assessment report [32]

Emissions scenario	Global mean temperature change (2090s relative to 1980–1999)	Global mean sea level rise (2090s relative to 1980–1999)
Low (B1 scenario)	1.8°C (1.1–2.9)	18–38 cm
Medium (A1B scenario)	2.8°C (1.7–4.4)	21–48 cm
High (A1FI scenario)	4.0°C (2.4–6.4)	26–59 cm

Conversely, many regions are uplifting and this will tend to offset some sea level rise. Some cities are also exposed to human-induced subsidence, mainly due to groundwater withdrawal and drainage of coastal soils. These effects can be at a similar or greater scale than human-induced sea level rise; for example, during the twentieth century Tokyo subsided by up to 5 m, Bangkok by up to 2 m, and New Orleans by up to 3 m. Some cities can also experience increases in storm surge risk from the removal of natural coastal protection, such as wetlands. Subsidence throughout the greater New Orleans area has complicated future protection and restoration designs [13, 38]. Coastal erosion can exacerbate climate change impacts and may also be intensified by sea level rise and rising storm surge hazards.

20.3.2 Climate Change and Uncertainty in Coastal Regions

20.3.2.1 Sea Levels

Global sea levels rose at an average rate of around 1.8 mm per year from 1961 to 2003. This rate accelerated to about 3.1 mm per year during the last decade (1993–2003), but it is not yet clear if this reflected an acceleration of the long-term trend or natural variability [32]. What is clear is that sea levels are rising much faster than expected from modeling studies, largely due to unanticipated changes in ice flows in the world's major ice sheets over the past decade [68].

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) projects a global sea level rise of 18–59 cm by the end of the twenty-first century (Table 20.2). Due to lags in the climate system, a significant fraction of this increase is already committed to from past emissions. This range is likely to be an underestimate; the models used to produce this estimate omit processes that are known to be important, such as changes in flows of ice sheets. Considering these processes, the IPCC AR4 suggests that sea level rise in 2090s could be around 0.1–0.2 m greater than these projections. A number of studies have questioned whether the IPCC ranges are still too conservative. For example, Rahmstorf [68] applied a semi-empirical approach to modeling sea levels based on historical data and IPCC global temperature projections and produced a projected a sea level rise of 50–140 cm by 2100.

For adaptation decision making it is also important to note that anthropogenic global warming during this century could trigger changes in the world's ice sheets that would commit the world to much higher levels of sea level rise in later centuries.

Without adaptation, sea level rise alone will increase losses related to storm surges in coastal regions. For example, recent research by Risk Management Solutions and Lloyd's of London [48] has indicated that even a sea level rise of 30 cm could drive a doubling of average annual losses from storm surge for individual properties in exposed coastal regions, and an increase of about 10–20% in 1-in-200-year losses. Additional increases in hurricane activity would drive losses to higher levels.

20.3.2.2 Changes in Storminess

The rarity of tropical cyclones and extratropical storms and the short length of current records make it difficult to detect statistically significant trends in these events. For example, since 1995 we have experienced a period of high hurricane activity in the Atlantic Basin, but it is not clear to what extent this is due to human-induced climate change or natural variability [44]. Nonetheless, basic physics tells us to expect a greater frequency of high-intensity extreme events in a warmer world.

A number of research groups have used climate modeling to explore possible future scenarios. For example, new research by Bender et al. [7] suggests that while overall annual numbers of Atlantic tropical cyclones could decrease, the numbers of the most intense (Category 4 and 5) hurricanes could increase significantly. For the 18-model ensemble-mean climate change, they found an increase in the frequency of Category 4 and 5 storms that corresponds to a 10%-per-decade linear trend over this century. These numbers are subject to uncertainty, but a growing number of studies point to a similar picture of future hurricane activity in a changing climate [24, 54].

The effect of such changes on losses would be amplified as they are typically nonlinearly related to levels of hazard. For example, research by the Association of British Insurers [4] concluded that an increase of just 6% in wind speeds could increase average annual insured property losses in the U.S. from hurricanes from US$5.5 billion to around US$9.5 billion.

Changes in the characteristics of winter storms are also highly uncertain. Most studies project a poleward shift in the storm track, but the extent of this shift and changes in the frequency and intensity of storms remains uncertain. Again, any increase in intensity is likely to nonlinearly affect levels of risk.

20.4 *People Matter*: Participatory Approaches in Adaptive Design

A fundamental aspect of human/climate interactions is to recognize that people have been reacting to changes in climatic conditions for centuries through a variety of actions such as land use changes and migration. This is not to imply that humans necessarily react optimally to these drivers. As an example, people may not want to move away from their ancestral homes even though local environment is damaged or at risk. Our working group established that this "people factor" highlights a critical need for a participatory approach to decision making and implementation of adaptive options in society. This approach seeks to engage people in discussions on risks and options at an early stage to define the problem and understand local values, then encourage adoption of adaptive alternatives. In addition, this approach should stress the importance of understanding the role of cultural influences in participatory decision making.

Human drivers of risk may be equal to or greater than climate drivers of risk; for example, through demographic shifts or land use changes. It is crucial to define the human dimensions of vulnerability to fully understand risk in terms of who is vulnerable and what environmental and socioeconomic factors drive vulnerability. In this light, self-interest is an important driver of adaptation and there is role for government in supporting self-interest and avoiding maladaptation through information and technology transfer, and in fostering collaboration and brokering collective action (action by many is normally cheaper and more effective than action by one). A key question is how to move from adaptation to adoption: a key part of adoption is autonomous adaptation—but autonomous adaptation actions by people are often considered a barrier to adoption. Adoption can be facilitated through collaboration and participation in the decision process—engaging people in decisions so that they see that their values have been understood and reflected in decisions, understand the process and its reasons and implications, and therefore support and actively participate in decisions.

20.4.1 People Making Decisions: Decision Analysis and Human Judgment Under Uncertainty

Decision analysis can provide a useful analytical framework and suite of tools for contributing to better decisions by helping decision makers and participants structure the problem, balance risks, and compare options based on outcomes and expressed preferences [25, 33]. The primary focus of these decision analysis techniques is the identification of tradeoffs among potential alternatives. Kiker et al. [40] provide a review of various multicriteria decision analysis (MCDA) techniques as well as their implementation within environmental risk analysis applications.

Within environmental simulation, we face a decision point: to make more detailed and complex decision tree structures to auto-manage complex systems or to simplify the incoming system data into a few heavily tested and analyzed metrics for a set of decision heuristics. In other spheres, this conflict is mirrored by the "Heuristics and Biases" approach [35, 36] and the "Fast and Frugal Heuristics" framework [26, 27].

More recent developments in cognitive psychology have focused on the adaptive strengths of humans in their decision making [17, 18, 26, 27]. These authors argue that limitations described by Kahneman and Tversky [35, 36] are in actuality the evolutionary framework of an adaptive toolbox of useful decision heuristics to efficiently sort and process the large amount of information entering human cognizance. Gigerenzer et al. [27] point out sets of basic heuristics. Within an environmental context, Anderson et al. [3] provide useful examples of adaptive decision facilitation and problem solving under uncertainty using Bayesian methods, adaptive management, and evolutionary approaches. Along these same lines, Gual and Norgaard [29] propose a co-evolutionary framework for bridging the gaps between biological and social sciences. Evolutionary principles derived from biological sciences do not easily mesh with sociocultural change theories, thus making co-evolutionary constructs tentative and preliminary. The authors propose that ecological economics provides foundation for managing co-evolutionary biophysical, biotic, and cultural forces that both influence and are influenced by each other.

20.5 *Governance Matters*: Challenges and Changes Within Institutions

Meadowcroft [53] points out features of climate change that create significant challenges for governance through societal reach, scientific uncertainty, distribution and equity linkages, long timeframes, and global implications. People and their institutions can be a barrier to adaptation, but institutional innovation is possible. It is important to understand the decision space; that is, the constraints and operating environment of decision makers. Coastal governance is often an interagency issue within decision making and implementation where authority is devolved into a mass of agencies and departments with different values and objectives. This chopping up of responsibilities can limit governance and institutional options to deal with risks as one agency does not tend to own the problem or the whole solution. Current institutional arrangements and decision-making frameworks often do not facilitate or allow the open flow of information from science to policy and thus there is no clear way in for new science to influence governance structures. In this light, there is a significant need for institutional innovation to consider new structural and non-structural arrangements for collaborative adaptation.

20.5.1 Public and Private Sector Adaptation

The nature of planning and risk management in coastal regions means that coastal adaptation in NATO countries will be mainly a government-led activity. Adaptation is also likely to be primarily government-funded (e.g., for adapting public infrastructure, shared coastal protection, and early warning systems), but will include some private financing, such as for port and harbor upgrades [66], retrofitting individual private buildings (and some private protection measures), and purchasing insurance.

An important role for public policy is to help overcome the barriers to private-sector action on climate change [20]; for example, to create the right incentives to ensure that current long-term investments are climate-proof. Important barriers to adaptation include: information (not understanding the risks or having adequate information to deal with them); financial constraints; and myopia (focusing on short-term goals, rather than long-term sustainability). The public sector can play an important role in overcoming these barriers through, for example:

- **Provision of information:** for example, the UK Climate Impacts Programme (a government-sponsored program) distributes free information on climate change projections and adaptation tools, as well as holding seminars and maintaining an interactive website to support users. Similarly, the Association of British Insurers publishes information on flood resilience for homeowners.
- **Regulation:** for example, controls on new developments and land-use planning, and building codes, utilized extensively today across NATO countries.
- **Financial incentives:** for example, grants to support retrofitting properties against storm surge hazards. In many countries these are becoming available for supporting low-carbon transition, but adaptation incentives remain minimal. Other incentives could include those that would help to build a market for resilient homes by reflecting adaptation and risk in property and insurance prices.

Finally, we note the importance of considering incentives that may act against adaptation and actually increase risks; for example, tax-based incentives that encourage homeowners to move into hazardous areas. An example studied in the literature is the provision of public-sector insurance, such as the National Flood Insurance Program and Citizens in Florida, which tends to homogenize insurance pricing (largely for equity and affordability reasons) and so may be a disincentive to risk reduction investments [45].

Risk sharing, such as insurance (public or private), can play an important role in adaptation [31]. Insurance provides a predefined financial payout to the insured in the event of a loss, in exchange for an annual premium. Insurance can be an important adaptation tool by reducing the impact of a hazardous event on the individual (or group, in the case of collective insurance initiatives). However, insurance is not a substitute for risk reduction: it cannot prevent direct damage, injury, or loss of life; it can only provide a financial compensation to aid in repair and recovery after an event occurs. For this reason, insurance is most economically and socially effective where it is applied as part of an integrated risk management approach. Where insurance is applied without adequate risk reduction, it can actually be a maladaptation; as when individuals rely on insurance entirely to manage their risks and are left exposed to impacts. Herweijer et al. [31] highlight that properly designed insurance initiatives can help to create incentives for risk reduction. Insurance premiums based upon the technical price of risk can provide an important risk signal to policyholders to undertake adaptation measures.

Finally, we note that insurance itself is vulnerable to climate change, particularly in coastal areas where hazard levels are already high and exposures are strongly accumulated. Herweijer et al. [31] demonstrate that rising hazards, where not compensated by adaptation, will lead to increased insurance premiums, and in the long-term, the potential for a loss of insurability. Adaptation is, therefore, important in helping to maintain the accessibility and affordability of insurance in the face of rising hazards.

20.5.2 Tools for Exploring Adaptation Options and Costs

Adaptation options can reduce risks through either reducing exposure to coastal hazards (i.e., the people, property, or ecosystems in areas susceptible to coastal hazards), or reducing vulnerability (i.e., the impacts of hazards when they occur). Parry et al. [66] reports on three categories of planned adaptation options:

1. **Managing exposure:** impacts on human systems are limited by moving populations back from the coast, preventing new building in exposed regions, and using land-use planning and development controls. In some cases, this can also benefit natural ecosystems by removing human pressures and allowing species the space to naturally migrate.
2. **Accommodation:** impacts on human systems are limited by reducing vulnerability to coastal hazards; for example, increasing flood resilience (e.g., raising homes on stilts), strengthening buildings against wind damage, establishing early warning systems, and risk sharing (e.g., insurance).
3. **Protection:** the impacts of sea level rise are reduced by soft or hard engineering (e.g., nourishing beaches and dunes, or restoring natural wetlands or sea walls). Risk cannot be completely eliminated by protection.

It is impossible to build a complete picture of the potential costs of adaptation in coastal regions. Nicholls [57] summarized a number of estimates for specific components of risk management today from across NATO countries, mainly related to coastal protection. For example, in England the total Flood and Coastal Management budget is roughly £250 million per year. This is expected to reach £1 billion per year by the 2030s. The Thames 2100 project alone, an appraisal of flood management options for London to 2100, cost around £15 million. Japan invested 120–150 billion Yen per year from 2003 to 2006. The Netherlands invests an estimated $600 to $1,200 million per year on coastal risk management.

Looking forward, Agrawala et al. [1] provide a summary of estimates of the costs of adaptation in coastal regions. To select just a few: EC 2007 estimates costs for Europe of €1.3–4 billion per year in 2030 and €1.3–9.3 billion per year in 2080, where ranges depend on the emissions scenario. Estimates from Nicholls [57] and Tol [84] range from $0.5 to $1.8 billion per year. For North America, estimates by Nicholls [57] and Tol [84] range from $0.8 to $2.0 billion per year. These types of estimates are not comprehensive and likely to be underestimates; for example, they typically use an optimization approach and incorporate only sea level rise and one adaptation option (usually raising dikes). They also tend to assume that coasts are optimally adapted today and that defenses are in good order and can be upgraded with climate change. In many cases, particularly in developing countries, these assumptions could be considered optimistic. Even in cities like New York, it is likely that there is a substantial gap between existing protection systems and the optimum [66]. The Nicholls study [57] uses a modest sea level rise scenario (only 44–53 cm in 2080); UK or Dutch projections would increase costs significantly. Tol [84] assumes 1 m sea level rise. Incorporating other trends, such as changes in storminess and subsidence, would also increase costs.

A number of studies have produced estimates of the global costs of adaptation in coastal regions. Nicholls [57] estimated adaptation costs of $4–11 billion USD per year in 2030 (anticipating needs to 2100). Residual impacts were estimated to increase from $6 billion per year today to $8 billion per year. Tol [84] estimates costs of adaptation using a similar approach of $11 billion per year.

20.6 *All Is Not Lost*: Integrated Tools, Processes, and a Case Study for Coastal Adaptation

While no single tool, action, or option provides integrated coastal planning for climate change, a suite of tools are currently available for decision makers to explore potential adaptation options. This discussion highlights a few of these tools to begin problem framing at the start of a decision process. This early organization is particularly important for identifying objectives and values, but is also critical for helping scientists and decision makers to work effectively together. Figure 20.2 highlights the role of planning where data and stakeholder inputs are critical to the decision/risk analysis process. Valuing information plays a critical part in designing adaptation plans. Identifying the right information and research needs to support better decisions is particularly important in analyzing the sensitivity of decisions themselves to the science. This process helps to identify important assumptions and missing processes that may have a high impact on the decision (e.g., would including sediment processes in a computer model change the decision?)

20.6.1 Tools for Assessment and Management of Adaptation Efforts

Development of useful decision tools should move beyond simply creating ever more complex models for simulating coastal physical processes. The NRC [62] provides six principles for effective decision support regarding climate change:

1. Begin with user needs.
2. Give priority to process over products.
3. Link information producers and users.
4. Build connections across disciplines and organizations.
5. Seek institutional stability.
6. Design processes for learning.

Fig. 20.2 Example of a "context first" approach to adaptation decision making [69]

Macey [51] promotes both the invention of new methods and the refurbishment of existing frameworks to help in the formulation of adaptive responses to complex environmental challenges. Like most complex socioecological systems, coastal areas will integrate both physical and social processes ranging from sediment management to cultural values. Kiker et al. [40] focus on the need for people, process, and tools as three fundamental elements of environmental decision making. Bammer [5] provides a useful conceptual design for an integration and implementation science which combines combinatorial disciplines systems theory and complexity science with participatory methods and adaptive learning.

Community-based initiatives are more empirically focused on community values, capacities, and resources [64, 65, 83]. While particularly useful to mobilize community attention and resources to a specific set of issues, they may not be designed to be scaled up or linked with other policy efforts [81]. Lynham et al. [50] provide a useful review of tools for incorporating local knowledge and learning into decision making within natural resources ranging from Bayesian belief networks and dynamics models to discourse analysis to Venn diagrams. Lynham et al. [49] provide a practical example of linked river and reef adaptive modeling combining expert and stakeholder perspectives for the Great Barrier Reef Region in Australia.

20.6.1.1 Scenario Analysis

Scenario analysis comprises a powerful methodology to think about uncertainty and risk. This kind of framework assists teams in analyzing past and present trends, detailing possible future developments, and using the insight gained to explore potential actions designed to improve the current situation. Scenarios are a testbed in which an area of policy is considered and judged [87]. They have been used extensively over the past four decades by business and government to think systematically about the future and to make decisions in the face of uncertainty [14, 34, 43, 47, 71, 72, 74, 79, 80]. More recently, stakeholders and scientists involved in ecological conservation have begun to see the usefulness of scenario planning as a way to deal with the complexity and uncertainty of environmental decision making [8, 55, 67, 70, 90, 91].

20.6.1.2 Adaptive Learning and Management Frameworks

Adaptive management [61, 89] has been increasingly adopted (at least in abstract principle) by many resource management agencies as a practical way to embrace uncertainty and move forward via institutional learning. This environmental monitoring and evaluation framework describes resource management decisions as an active experimentation process with system learning as a primary benefit. Both active and passive adaptive management constructs highlight the evolutionary role of adaptation and new learning as a vital part of the decision making process. Lee [46] provides a useful critique and descriptions of learning theories for different philosophies and group sizes as a guide to social learning within various institutions.

In a more recent approach, Olsson and Folke [63] promote an adaptive co-management (AC-M) framework which incorporates adaptive management with participatory, cooperative management to acknowledge the importance of shared responsibilities and rights of stakeholders [73]. An important foundation of AC-M is the recognition that different scales of governance should work in a cooperative fashion to assure successful management. The complexity of institutional designs and collaboration patterns amongst stakeholders presents a significant challenge that increases uncertainty with increasing geographic and human relation scales [82].

Anderson et al. [3] presented a useful description of adaptive decision making and its relationship with uncertainty. In addition, the authors highlight the linkage of decision heuristics with internal and external social contexts to help select the most appropriate form of adaptive management. A significant challenge to advocates of adaptive management is the accounting of various social and institutional drivers that may destabilize the foundations upon which the adaptive framework is constructed.

With respect to actual adaptive management implementation within existing resource management efforts, the role of uncertainty has created a critical point of human/model interface where the computational models are now providing increasingly sophisticated levels of uncertainty analysis (in terms of both model sensitivity and variation of simulated results), while humans are seemingly static in their ability to comprehend and manage these disparate streams of incoming information. Institutional learning pedagogies are rarely included in adaptive decision making frameworks, with groups usually opting for a reactive, problem-fixing methodology rather than a proactive problem/solution-visualizing process as envisioned by its original designers. Gunderson [28] highlights the development of an adaptive learning framework for the Everglades restoration, a complex megaproject that has endeavored to transform assessment into adaptive planning and execution. Walters [88] viewed the institutional failure of adaptive management efforts in fisheries management as:

> … i) lack of management resources for the expanded monitoring needed to carry out large-scale experiments; ii) unwillingness by decision makers to admit and embrace uncertainty in making policy choices; and iii) lack of leadership in the form of individuals willing to do all the hard work needed to plan and implement new and complex management programs [88].

20.6.2 Adaptation as a Verb: Action and Evolution Within Decision-Making Processes

Adaptation in coastal systems has a number of characteristics that call for a rigorous and structured process of decision making under uncertainty. These characteristics include:

- **Sea level and climate conditions will continue to evolve over long time periods and the scale of potential changes is large.** The world is already commited to further changes over the coming decades. The impacts of changes in sea level and storminess could increase nonlinearly with rising hazards.
- **The uncertainties in sea level and future storminess could be characterized as deep uncertainty**: while projections exist, science has not fully characterized the range of possible futures and it is currently not possible to attach probabilities to projections with a degree of confidence.
- **Coastal property and infrastructure typically have long lifetimes, long lead-times, and high sunk-costs.** This means that the potential costs of maladaptation are high in terms of (i) the costs of prematurely retiring or retrofitting property and infrastructure that has been underadapted to climate change, as well as the potential unnecessary damages to property and risks to lives and livelihoods; and (ii) the potential for unnecessary costs from overadapting.

In discussing adaptation, it is important to note that climate change is just another risk factor (albeit an increasingly important one) in decision making [2]. It must be taken into account in decision making alongside regulatory, commercial, social, political, and macroeconomic risks. Similarly, adaptation objectives must be considered alongside broader objectives; for example, economic and human development. This is particularly relevant in coastal regions. The coasts are desirable areas for human settlement and economic activity in many regions; these needs must be transparently and rigorously weighed against the risks of climate change and the costs of adaptation.

20.6.3 Living and Working with Uncertainty: The UK Thames 2100 Project—A Case Study for Integrating Uncertainty, Climate Change, and Coastal Systems

While coastal areas face significant uncertainty, this does not have to be a barrier to exploring adaptation measures in the near and long term. The Thames 2100 Project was run by the UK Environment Agency and aimed to provide a plan to manage tidal flood risk in the Thames Estuary over the next 100 years. The study focused on the adequacy of and options relating to the Thames Barrier, a large flood barrier that protects London from North Sea storm surges. The Thames Barrier was built in response to the 1953 surge disaster and was designed to meet at least a 1-in-1,000-year standard of protection until 2030. The Barrier opened in 1984; due to its long lead-time for planning and building (31 years), the Thames 2100 project was instigated in 2000. The analytical project was completed at the end of 2009 and is now being used to inform decision making for London. A report of the project is given by Haigh and Fisher [30].

The Thames 2100 project is a relevant case because it was one of the first very large-scale projects to fully recognize the scale of the uncertainties in climate projections (i.e., the ambiguous nature of uncertainties) and implement a structured and comprehensive decision-making approach. This was necessary as the project incurred high sunk-costs, its decisions have a long lifetime, and the decisions were found to be highly dependent on the uncertain climate projections. The MCDA approach assessed not only the economic costs and benefits of different options, but also their effects on other performance metrics, such as people at risk and environmental impacts.

The economic component of the decision analysis was based on real-options theory. This allowed the plan to focus on assessing the appropriate sequencing of options to facilitate flexibility in the adaptation process. The first stage of the project was to map out the plausible range of climatic changes and then identify several potential solutions relevant across this range. These options ranged from enhancing the current Thames Barrier to building an entirely new barrage further up the estuary. The project identified a number of adaptation pathways (High Level Options or

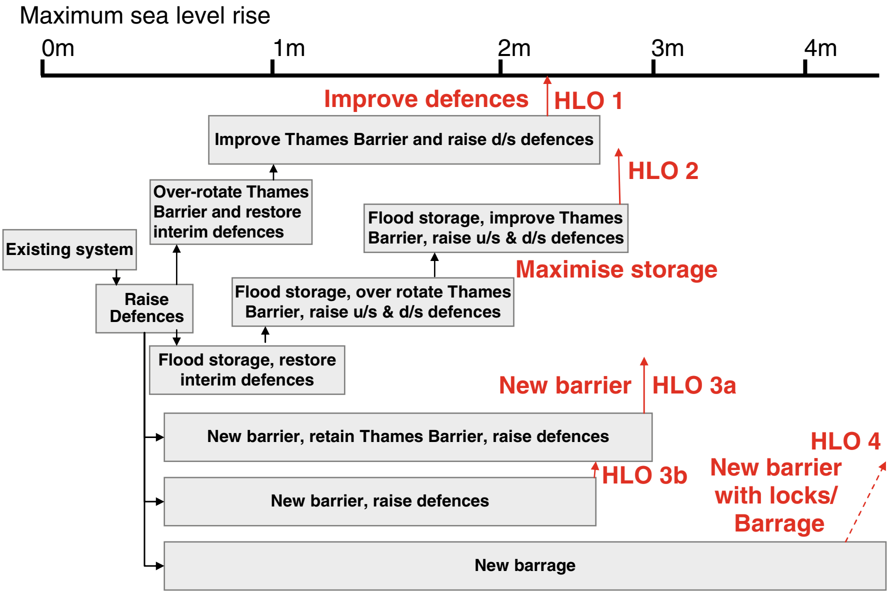

Fig. 20.3 Identification of adaptation options and pathways in the Thames Estuary 2100 project [30]

HLOs) (Fig. 20.3) and found that it was possible to move from one pathway to another, with decisions depending on the actual rate of climatic changes observed. Decisions on shifts between pathways could be linked to critical lead times for specific adaptation measures. This demonstrated that a flexible approach was possible.

A challenge faced by the project was whether to recommend a single pathway now, or to suggest a wait-and-monitor approach. A real-options approach was applied to weigh the cost implications of specifying a pathway now versus waiting for more information on projected rates of sea level rise. The analyses found, for example, if a wait-and-monitor approach is followed, leaving a decision to around 2050, then the expected payoff of the decision is around £210 billion, implying a value of waiting of around £14 billion. Similar conclusions were found under different sets of assumptions, leading the project to conclude that a wait-and-monitor approach was desirable. This approach is possible in this case because proactive risk management in the Thames Estuary over the past 50 years, including flood walls and land planning policies, have maintained the robustness of the flood risk management system to changing hazard levels.

The study also considered the limits to adaptation in London; that is, the maximum amount of sea level rise that could be accommodated by coastal protection systems without incurring a significant change to the structure and functioning of the city of London. A study suggested that for London this limit was around 5 m.

This is far outside of the current planning horizon (out to 2100), but within millennial-scale projections if, for example, the West Antarctic or Greenland ice sheet were lost. Above this level of sea level rise, a retreat strategy may become necessary.

20.7 Discussion: Research Gaps and Opportunities

The objective of this chapter was to highlight major issues within coastal adaptation to climate change and to provide an initial introduction and discussion of more systematic adaptation decisions and policies within complex socioecological systems. In terms of vulnerability and adaptation definitions, a rich literature describing various methodologies is available to aid policy and practice in categorizing elements of exposure and assessing elementary, unidimensional effects. However, within complex environmental challenges, there has been a distinct lack of integration between academic assessment and research and practical decision making. Within technically focused projects, cognizance of any sociopolitical factors is usually assumed into static irrelevance or ignored entirely in the interests of getting the best possible science. Often there seems to be a prevailing idea on the part of scientists and engineers that decision makers and stakeholders will be able to recognize and appreciate the power, nuance, and uncertainty contained in a set of best-possible-science results. An interesting paradox of the best-science narrative is that if scientists and engineers are overly confident in their results, any changes or modifications to their conclusions may cause them to lose face or status in their role of providing relevant data to decision makers. Alternately, if they are overly hesitant in reporting their results because of lack of information, its variability, or its inherent uncertainty, they are accused of being evasive, opaque, or even incompetent. Often the result of these tools are interesting in an academic sense but are not accepted by decision makers in reality. As a result, in practice most model results are fed into more ad-hoc decision-making approaches [40]. Cortner and Moote [21] present a useful set of 10 policy paradoxes that review the seemingly contradictory existence of competing objectives within natural resources management. For example, expert and open decision making contrasts the objective of using the best possible science coupled with active decision roles for diverse stakeholders. While the two objectives may coalesce into agreement, they just as often do not, requiring technocratic or consensus tradeoffs.

In terms of professional practice, state-of-the-art concepts (as delineated in the academic literature) and state-of-practice methods (as described in most site-based, technical reports) are still quite far apart. Practical application of sophisticated adaptive decision methods are rarely attempted given the typical constraints of time, budget, and political pressures. Newer methods of interaction focus on the iterative nature of model development and incorporate model development as part of the practical decision environment for complex ecological challenges [19, 22, 41, 42]. In terms of adaptation processes, the integration of results needs to be credible, transparent, adaptable, and repeatable, with a structured and defendable (and ultimately adaptive) decision as the ultimate goal. The Thames 2100 case study is an attempt to document the merging of state-of-art and state-of-practice for coastal adaptation projects.

Most coastal restoration/protection projects undertaken by federal resource agencies are replete with uncertainties. In some cases, system quantification methodologies (hydrologic and hydraulic, sediment transport, water quality, ecological, and other models) have been unavailable, inaccessible, expensive, and insufficient. As a result, unstructured and undocumented ad-hoc decision methods have been relied upon to fill the information gaps within analysis and planning methodologies when faced with limited time and budgetary resources. Many decision tradeoffs are constructed on simplified assumptions or heuristics that are either set by current and immediate issues or left to researchers to suggest. The result is often adaptive policies that are either too prescriptive or inconsistent among different societal populations.

The path forward will be to create favorable conditions for specific, adaptive, and practical decision support and risk analysis tools to aid planners and participants in developing technically accurate and functionally efficient adaptation policies. These methods will help to ensure a collaborative and learning-focused planning process that will help tame complex coastal challenges.

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Chapter 21
U.S. Army Corps of Engineers Approach to Water Resources Climate Change Adaptation

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Abstract The magnitude of climate change impacts facing water resources managers in the United States has spurred closer interagency cooperation in developing methods supporting planning and engineering for climate change adaptation. The two largest water resources management agencies in the U.S., the U.S. Army Corps of Engineers and the Bureau of Reclamation, have partnered to describe climate change challenges, identify user needs for improving tools and information, and assess capabilities to use weather and climate forecasts in federal water resources management. They have also hosted a forum with national and international experts exploring the issue of nonstationary hydrology with respect to climate change. In progress is development of multiagency guidelines for best practices to select from the portfolio of climate information including global climate scenarios, through general circulation models, through downscaling, to regional or watershed-scale hydrological and operations planning models to account properly for climate change and variability at the scale of water-resource operational decisions. This presentation describes collaborative activities and the resulting methods being used as both agencies plan for and implement climate change adaptation measures.

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21.1 Introduction

The importance of water as a fundamental requirement for life and economic development has resulted in water resources management frameworks that improve the capacity of water managers to absorb change without unduly impacting basic functions while allowing them to balance competing needs [16]. Water managers thus provide a potential reservoir of resilience for operations in the face of climate change, *if* they are prepared to act effectively in a timely [33] and collaborative manner [22]. Water resources planning, engineering, and design are important factors determining the sustainability of projects over their life cycle, and are key elements in management strategies to improve resilience.

The two largest water managers in the U.S., the U.S. Army Corps of Engineers (USACE) and the Department of Interior's Bureau of Reclamation (Reclamation) recognize that an unprecedented level of collaboration is necessary to meet the combined challenges of climate and global change to water resources management. The agencies are developing and implementing strategies to "manage the unavoidable" climate change effects through planning, engineering, and design of climate change adaptation measures that can also protect against adverse effects of other global changes. This collaboration brings together two agencies with long experience in adjusting to meet new water resource-related challenges. Since 2006, the relationship has proved beneficial to these water managers, their partners and stakeholders, and presents a model for other nations.

This paper describes the USACE collaborative approach to preparing for climate change and the resulting methods being used as we plan for and implement climate change adaptation measures.

21.2 Roles of USACE and Reclamation in U.S. Water Resources Management

The two largest water resources management agencies in the U.S. are USACE and Reclamation, each having different yet complementary missions and responsibilities. Operating continuously since 1802, USACE operates nationally and internationally, while Reclamation has operated in the seventeen western states since 1902 (Fig. 21.1). The administrative boundaries of both agencies generally coincide with major river basin boundaries, with the exception of Reclamation's eastern boundary.

Nearly every mission of the two agencies is already or very likely will be impacted by climate change, which affect design and operational assumptions about resource supplies, system demands or performance requirements, and operational constraints [1]. USACE and Reclamation have shown remarkable resilience in the face of previous environmental and operational changes, but the profound effects of climate change could overtax their capacity and may confound existing challenges.

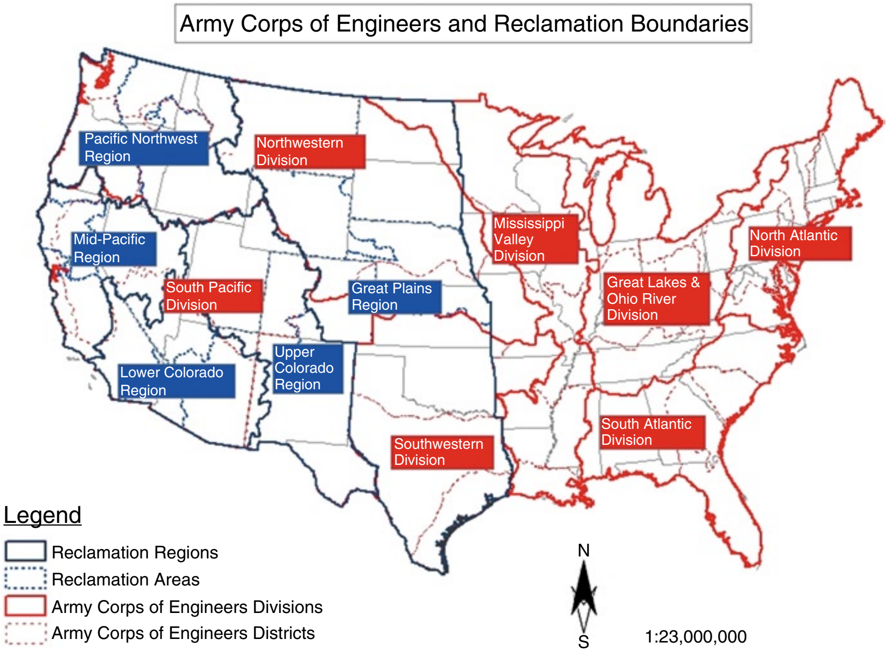

Fig. 21.1 Management of the nation's largest water resources managers (USACE and Reclamation) is organized largely by major river basins

In part because Reclamation and USACE have some similar and some distinct responsibilities, effective and efficient water management requires coordinated and consistent responses to climate change by the two agencies. Both agencies have a strong life-safety component to decision making. At each agency, the commitment to life safety was reevaluated and strengthened by internal and external analyses following tragedies: the Teton Dam failure in 1978 for Reclamation and Hurricane Katrina in 2005 for USACE. In both cases, strengthening professional and technical competencies was a priority. The ability to incorporate new and changing information, such as climate change, was a particular concern of the Interagency Performance Evaluation Task Force [9] following Hurricane Katrina.

For all these reasons, Reclamation and USACE are partnering as they move forward to face the challenges posed by climate change to water resources managers [1, 3]. Both agencies recognize gaps between current and future capabilities required to respond to climate change. Some needs are common, while others are agency-specific, but all these needs will require improved resilience as the agencies include climate change in their water resources planning, engineering design, construction, and operations. A common understanding of how climate is changing, how these changes impact water management resilience, what climate change information is needed to evaluate impacts, responses, and adaptation, and how this information will be used, is fundamental for developing rational, consistent, safe, approaches based on best available—and actionable—science.

21.2.1 Agency Missions: Similar but Complementary

For more than 230 years, USACE has supplied engineering solutions for U.S. water resources needs, including for navigation, flood and coastal storm damage reduction, protection and restoration of aquatic ecosystems, hydropower, water supply, recreation, regulatory, and disaster preparedness and response. Approximately 12 million acres of land and water resources are under the jurisdiction of the USACE as part of its Civil Works portfolio of 2,500 water resources projects, programs, and systems. USACE also applies water resources management expertise to support military program operations worldwide that promote peace and stability.

Reclamation was established with a mission centered on the construction of irrigation and hydropower projects in the western U.S. that has evolved to include municipal and industrial water supply projects, water recycling, ecosystem restoration, site security, and the protection and management of water supplies. Through this evolution of its mission, Reclamation is involved with environmental impacts, changing demographics, and periodic drought in the 8.7 million acres they own and administer in the West.

The common missions of the two agencies (hydropower, dam safety and critical infrastructure, water supply, ecosystem restoration and protection, and recreation) are described in more detail below. The differing missions of the two agencies (e.g., navigation, flood and coastal storm risk reduction, regulatory, irrigation, disaster preparedness and response, and war-fighter support) all have a strong water resources management component and thus still share many of the challenges and needs of the common missions.

21.2.2 Common Mission Areas Impacted by Climate Change

21.2.2.1 Hydropower

Hydropower is perhaps the most similar mission area for USACE and Reclamation, which together provide a little more than half the hydropower in the U.S. According to Hall and Reeves [8], USACE and Reclamation own 78% of federal hydropower plants providing about 91% of federal hydropower capacity. USACE operates 75 major hydropower projects, with nameplate capacity of more than 21.75 GW, supplying more than 24% of U.S. hydropower. An additional ~2 GW of installed capacity is available through nonfederal installations at USACE dams, a number likely to increase in the coming years. The second-largest producer of hydropower in the U.S. after USACE, Reclamation has nameplate capacity of about 13.56 GW, supplying about 18% of U.S. hydropower production. The Bureau of Reclamation and

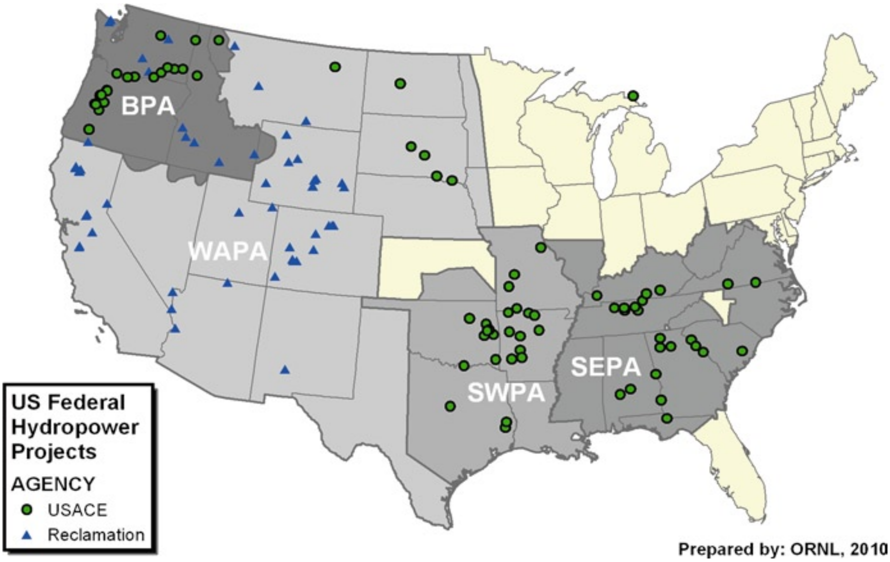

Fig. 21.2 Existing federal hydropower projects at Reclamation and USACE projects. Four power market administration areas are shown: Bonneville Power Administration (*BPA*), Southeastern Power Administration (*SEPA*), Southwestern Power Administration (*SWPA*), and Western Area Power Administration (*WAPA*) (Prepared by National Hydropower Asset Assessment Project Team, Oak Ridge National Laboratory)

the U.S. Army Corps of Engineers share hydropower production within the Columbia and Missouri River Basins. Figure 21.2 shows the location of federal hydropower installations at USACE and Reclamation projects.

Hydropower production is typically operated using sub-hourly weather information but does also rely on climate forecasts and projections on scales ranging from monthly to multidecadal. Operating hydropower projects with multiple purposes (e.g., flood risk reduction, irrigation, municipal and industrial water supply, navigation, in-stream flow augmentation, or recreation) requires knowledge of the full range of hydrological and meteorological climate change impacts as well as the expected frequency of these projected impacts. Though stationarity—the assumption that future hydrologic events will occur within the historically recorded range of variations in frequency and intensity—is an important factor in planning future hydropower operations, recent studies [12] indicate that the potential for nonstationarity must be considered.

21.2.2.2 Dam and Critical Infrastructure Safety

USACE has more than 600 dams nationwide and Reclamation has approximately 500. These agencies have begun standardizing their approaches to dam safety in ways similar to their partnering on climate change effects. Reclamation and the

USACE are in development of similar risk-based tools and approaches for assessing downstream consequences from natural hazards. Climate change effects on hydrologic stationarity can potentially result in changes to design inflows and outflows at projects that may affect safety. This is because often the upper estimates of risk for a dam are based on the Probable Maximum Precipitation (PMP) that could occur. The PMP is based on the moisture content in the atmosphere, which will change as air temperature warms and the thickness of the atmosphere changes.

A joint Reclamation and USACE project is exploring the potential changes in PMP through an analysis of dynamically downscaled climate projections from the North American Regional Climate Change Assessment Program (NARCCAP). An additional joint project between Reclamation and USACE is exploring reasonable methods for the use of climate projections to assess changes and vulnerabilities of current practices. An important aspect is characterizing probabilistic flood risk affecting other critical infrastructure such as levees. Other USACE critical infrastructure will benefit from this collaborative work, including more than 250 navigation locks and about 8,500 miles of levees, together with associated flood gates, pumping stations, and other components.

21.2.2.3 Municipal and Industrial Water Supply

As noted above, water supply is a primary mission for Reclamation, but a secondary mission for USACE. Reclamation is the largest wholesaler of water in the U.S., supplying water to more than 31 million people. Reclamation projects provide irrigation water to one out of five western farmers (140,000) for 10 million acres of farmland, producing 60% of the nation's vegetables and 25% of its fruits and nuts. Reclamation delivers 10 trillion gallons of water to more than 31 million people each year from a total storage capacity of approximately 245 million acre-feet (MAF).

Water supply is an authorized use for the USACE as part of multipurpose projects, but is not currently authorized as a primary or single purpose for a project. The total capacity of major USACE lakes is about 329 MAF. There are 136 USACE projects with authorized municipal & industrial (M&I) water supply storage in 25 states plus Puerto Rico. Total authorized M&I water supply storage of more than 9 MAF is provided through 316 water supply agreements with states, counties, cities, industries, and private individuals. 48 USACE projects have authorized irrigation storage.

21.2.2.4 Ecosystem Restoration and Protection

Water managers carry out Reclamation's official mission to:

> …manage, develop and protect water and related resources in an environmentally and economically sound manner in the interest of the American public. [23]

In doing so, they incorporate ecosystem considerations (e.g., fish, wildlife, and other environmental factors), into their water and power operations. They include aquatic ecosystem requirements as they identify and plan for future consumptive and nonconsumptive water supply needs.

The USACE Civil Works program includes ecosystem restoration as a primary mission, with specific guidance dating to 1990 [6]. USACE ecosystem restoration can be categorized as restoration, protection, and stewardship of natural resources associated with its projects. USACE and the Nature Conservancy have been working together since 2005 on the Sustainable Rivers Project, which has resulted in operations at USACE dams to support ecologically sustainable flow, joint training, and tools to support evaluation of hydrologic regime alternatives. In 2008, USACE reaffirmed the integration of ecosystem in all its mission areas through the development of the Environmental Operating Principles [29].

21.2.2.5 Recreation

Recreation is a major economic benefit associated with the water resources managed by both USACE and Reclamation, which relies on adequate water quality, quantity, and ecosystem health. Reclamation receives more than 90 million visits per year at its 289 recreational areas, which include 350 campgrounds. USACE receives about 368 million visits per year at 456 lakes in 43 states, supporting activities such as fishing, boating, hiking, camping, snorkeling, whitewater rafting, mountain biking, windsurfing, and programs for people with disabilities. USACE recreation provides over 4,300 recreation areas with 101,000 campsites, 80% of which are within 50 miles of a large U.S. city. USACE lakes host a third of all freshwater lake fishing in the U.S., and support about 200,000 fishing tournaments per year. With some 3,800 boat launch ramps, 56,000 miles of shoreline, and 5,000 miles of trails, USACE host 20% of all federal government recreation visits on 2% of federal lands. Reclamation has approximately 6.5 million acres of land and water, most of which are available for public outdoor recreation. This includes 289 developed recreation areas that contribute approximately $6B per year to the economy and support about 27,000 jobs.

21.3 Collaborative Activities

Over the past several years, USACE and Reclamation have led and participated in a variety of collaborative activities directed at understanding the impacts of climate change and exploring possible adaptation measures for their complementary missions. The activities have also included other agencies, partners and stakeholders, for improving transparency and knowledge transfer. These activities are primarily related to inland hydrology affecting the operation of USACE and Reclamation projects, with one exception, sea-level change.

21.3.1 First Steps: Basin-Wide Studies

The Reclamation-USACE partnership on climate change activities began in 2006 when the USACE was directed by the FY06 Energy and Appropriations Act (PL 109-103) [25] to conduct:

> …at full federal expense, comprehensive analyses that examine multi-jurisdictional use and management of water resources on a watershed or regional scale.

These planning studies were intended to demonstrate true multiagency collaboration. Two different large-scale proposals centering on observed climate change impacts to western states were developed by USACE teams, both with Reclamation and other agencies. During the development of study proposals, Reclamation and USACE scientists and engineers formed relationships and learned how much they had in common as members of water resources operating agencies.

21.3.1.1 Western States Watershed Study

One of five basin-wide studies funded under PL 109-103 was the Western States Watershed Study (WSWS). The study proposal was prepared jointly by the three western USACE Divisions—Southwest Division (SWD), Northwest Division (NWD), and South Pacific Division (SPD) (see Fig. 21.1 for locations)—and the study proponent was the Western States Water Council (WSWC). The study area encompassed the three major western watersheds (Columbia River, Colorado River, and Missouri River) as well as many other significant watersheds. The study was designed to support the development of collaborative and strategic plans for implementing several recommendations contained in the Western Governors' Association (WGA) 2006 report "Water Needs and Strategies for a Sustainable Future" [3]. Reclamation and USACE worked closely together on the tasks related to federal infrastructure, and also on a pilot study led by the State of California to explore reservoir regulation.

The pilot study was particularly important because numerous studies since the mid 1980s showed that impacts from climate variability and change were particularly significant to snow-dominated western mountain watersheds [5, 7, 11, 13, 19–21]. The observed impacts had serious implications for water management operations, especially the extremes of flood and drought. Because snow was prominent among the impacts (e.g., reductions in spring snowpack, earlier snowmelt and peak runoff, loss of glacial mass, increases in streamflow in winter and decreases in streamflow in summer), there was a temptation by many to begin revising the projects' authorized reservoir regulation curves to respond to these changes.

But, decision making by operating agencies like the USACE and Reclamation about reservoir regulation, particularly when flood storage is involved, requires careful study and consideration of project authorizations and other legal issues. Brekke et al. [2] explored the use of risk-based planning to identify alternative operational strategies under climate changes and found that flood control constraints were critical in the development and evaluation of strategies. However, the pilot highlighted the need for further research on the role of flood constraints and potential study approaches.

21.3.1.2 Widening Collaborative Activities

A second proposal team, though unsuccessful in obtaining funding for a planning study, nonetheless found success in developing new relationships and networks critical for climate change. This group intended to develop and test a multijurisdictional approach to improve the collaborative process for managing water resources in the western United States in response to climate variability. They planned to build on existing networks through pilot studies in the Columbia and Sacramento-San Joaquin systems. The proposal included USACE district and Division contacts, a representative from the Washington Climate Impacts Group, and a Regional Integrated Science and Assessment (RISA) Center of the National Oceanic and Atmospheric Administration (NOAA). Other federal agencies included in the proposal are Reclamation, the NOAA National Weather Service, and the U.S. Geological Survey (USGS); nonfederal organizations include The Nature Conservancy, state partners such as California Department of Water Resources, and Canadian partners for the Columbia River project. Though the proposal was not funded, team members collaborated on a series of conference and journal papers [30, 31, 34, 35]. Team members also participated in reservoir operations studies in collaboration with the WSWS [2].

21.3.2 Defining the Federal Perspective

Over the past several years, Reclamation and USACE have made a intensive effort to encourage interagency activities related to climate change because they recognize that climate change impacts are critical to current and future water resources management, and that the challenges to water resource management posed by climate change cannot be effectively met by one agency acting alone. One major activity was to partner with the two major water resources data and science agencies—USGS and NOAA—to examine the effects of climate change on U.S. federal water resources management agencies. This effort resulted in a jointly authored report titled *Climate change and water resources management—A federal perspective* [1].

This document, published as USGS Circular 1331, is the first jointly prepared document by the four agencies, and features all agency logos and transmittal letters signed by leaders of all four agencies. It provides a uniquely federal view of climate change impacts, decision making, climate change adaptation, and identification of gaps and needs. Case studies of planning studies using climate information are presented, as well as a review of paleoclimate reconstruction and downscaling.

21.3.3 Describing Agency Climate Information Needs

USGS Circular 1331 includes a table of knowledge gaps identified by water managers at a February 20–21, 2008, federal agency workshop addressing capabilities for incorporating climate change into western U.S. water resources management (see NOAA [14] for more information). Knowledge gaps intended to drive future research and development scoping and framing were identified in two major categories: access to information and new capabilities. Water management users desired access to literature syntheses (both regional and application-specific) and climate projection data (particularly downscaled data). They also desired new capabilities to:

- Translate climate projection data into planning scenarios
- Assess the response of natural and social systems to climate
- Assess the response of operations and dependent resources
- Assess, characterize, and communicate uncertainties

This workshop, though initially focused on the western states, was the nucleus of the nationwide Climate Change and Water Working Group (CCAWWG).

CCAWWG was formed by Reclamation, USACE, NOAA, and USGS in 2008 to work with the water management community to understand their needs with respect to climate change. A second goal of CCAWWG is to foster collaborative federal and nonfederal scientific efforts address these needs in a way that capitalizes on interdisciplinary expertise, shares information, and avoids duplication.

21.3.3.1 Describing Climate Information Needed for Long-Term Water Resources Planning

In 2009, the CCAWWG began a two-phase process of identifying required capabilities, current capabilities, and gaps associated with incorporating climate change information into longer-term water resources planning and then developing strategies to meet these needs. The operating agencies (USACE and Reclamation), with additional input from the Environmental Protection Agency (EPA), Federal Emergency Management Agency (FEMA), and Federal Highway Administration (FHWA) prepared an assessment of user needs: *Addressing Climate Change in Long-Term Water Resources Planning and Management: User Needs for Improving Tools and Information* [3, 32].

This report provides a detailed discussion of the steps necessary to conduct resource management studies and hydrologic hazards evaluations, which are generally taken on the multidecadal time scale; it also summarized knowledge gaps as they relate to these types of studies and to the list of gaps presented in Brekke et al. [1].

New gaps identified included improved understanding and guidance (Table 21.1). Internal and external reviewers provided their perspectives on the user needs. Thirty respondents from seven federal agencies, one state, and one local government agency,

Table 21.1 Long-term planning needs associated with incorporating climate change information into longer-term water resources planning, as identified by Climate Change and Water Working Group

Long-term planning need	Description
Understanding	How to interpret observed historical climate variability and climate projections' simulated climate variability from daily to multidecadal time scales (see Sects. 21.3.3.1 and 21.3.3.2)
	Synthesis of sea level projection information and guidance on consistent use in planning for all Reclamation and USACE coastal areas (see Sect. 21.3.6)
	How climate change could impact potential evapotranspiration, and how that is represented in watershed hydrologic models
	How source water quality characteristics depend on climatic variables, and how dependencies may evolve in a changing climate
	How climate and/or land cover changes will change watershed sediment yield, changes in sediment constituency, and the resulting impacts on water resources
	How climate, land cover, and/or sedimentation changes will affect river and reservoir ice-event potential
	How to improve skill in simulating long-term global to regional climate
	How institutional realities currently control socioeconomic responses to climate variability, and could control socioeconomic responses under a changing climate
Guidance (see Sect. 21.3.5)	Strengths and weaknesses of downscaled data and the downscaling methodologies
	Strengths and weaknesses of available versions of spatially distributed hydrologic weather data
	Appropriate methods to relate planning assumptions to specific classes of climate projections, when deciding how to use retained projections in planning
	How to make decisions given the uncertainties introduced by considering climate projection information

and six nongovernmental agencies provided comments. The report, finalized in January 2011, will be followed by a report presenting the views of the science agencies, led by NOAA and USGS, on how to meet the identified needs. USGS and NOAA are currently conducting initial planning activities on the science agency response.

21.3.3.2 Describing Climate Information Needed for Water Resources Adaptation Planning and Operations

Water management planning, design, and operations also require climate information on the shorter time scale to guide sub-hourly to monthly, seasonal and annual decisions. USACE and Reclamation identified a need to improve capabilities to forecast and use climate variability involving fluctuations in climate conditions on these shorter time scales to enhance the ability of water managers and water users to plan short-term operations and water delivery schedules. To meet this need, CCAWWG is using a similar two-phase plan that includes a user needs report by operating agencies, followed by a report outlining a strategy to meet these needs by science agencies. Raff et al. [17] are currently preparing a user needs document: *Use of Weather and Climate Forecasts in Near Term Federal Water Resources Management: Current Capabilities, Required Capabilities, and Gaps.* This document provides a review of the current uses of weather and climate in short-term decisions followed by an assessment of current capabilities and gaps. Special attention is paid to risk and uncertainty analyses and communication. The document is expected to be finalized in 2011 following internal and external review.

21.3.4 Addressing Nonstationary Hydrology

One of the topics raised in USGS Circular 1331 was how to understand and incorporate nonstationarity concepts in planning and engineering design. Though engineers have long assumed a geophysical stationarity of hydrologic forces for making their long-range designs and plans, they also recognized that the assumption can be violated. Recently, Milly et al. [12] suggested that with climate change impacts increasingly being observed, it was now time to develop methods to deal with nonstationarity. This is particularly important in water resources management areas with a life-safety component such as flood frequency analyses and dam safety assessments. It is imperative that any new guidance be developed considering agency mission areas and needs to support consistent interagency interpretation and application.

In response to this identified need, USACE hosted a CCAWWG expert workshop on *Nonstationarity,*[1] *Hydrologic Frequency Analysis, and Water Management* in Boulder, CO, during January 2010 [15]. The organizing committee included representatives from Reclamation, USGS, NOAA, EPA, the International Center for Integrated Water Resources Management, and Colorado State University. International experts on climate change hydrology from the United Kingdom, Poland, Japan, Canada, and Greece joined members from the U.S. academic community, and agency representatives from FEMA, FHWA, NRCS, U.S. Forest Service, and Navy. Other attendees represented Denver Water, the Western Governors Association, Manitoba Hydro, and Quebec Hydro.

Discussions during the workshop addressed whether assumptions of stationarity are valid, the use of different statistical models in nonstationarity conditions, trend analyses, how to use the output from global climate models (GCM), and how to treat uncertainty in planning, design, and operations. This will result in a special

[1] Stationarity is defined by Milly et al. [12] as "the idea that natural systems fluctuate within an unchanging envelope of variability," worked while we had factors of safety, now we recognize that global and climate change expand the potential future states beyond the past and must take a dynamic, rather than equilibrium view.

issue of the *Journal of the American Water Resources Association*, which is part of our approach to develop peer-reviewed, legally justifiable methods to support water management. Other workshop outcomes are to initiate mechanisms for a continuing dialogue between water managers and scientists on methods to deal with the water resource-related effects of climate variability and uncertainty, and to formulate an action plan to produce practical guidance for water managers to develop, test, and implement methods. Reclamation and USACE will work closely to be sure the workshop outcomes result in usable information for the water management community.

21.3.5 Assessing the Portfolio of Climate Information

Among the first problems identified by USACE and Reclamation was the large discontinuity between the available science on climate and climate change on one hand and the dearth of information for using that information or guidance appropriately in decision making over important water resources choices. In an effort to develop a consistent water resources management agency approach to this issue, they, along with the other CCAWWG agencies, conducted a workshop in November 2010. The workshop (*Assessing a Portfolio of Approaches for Producing Climate Change Information to Support Adaptation Decisions*) will help characterize the strengths, limitations, variability, and uncertainties of approaches for producing and using climate change information to inform U.S. federal water resources adaptation planning and operations [4]. The desired outcome is a strategy to develop guidance that provides principles and approaches for assessing the strengths and limits of the various methods for producing and using climate information at specific choice-points. Ideally, the guidance will be structured to be flexible enough to apply to current state-of-the-science information as well as to future developments as climate science moves ahead.

21.3.6 Sea-Level Change Considerations

USACE has had a sea-level change policy in place since 1986, incorporating information contained in the National Research Council's 1987 report *Responding to Changes in Sea Level: Engineering Implications*, a study supported in part by USACE. Following Hurricane Katrina, USACE identified a requirement to develop a standardized vertical datum and to update the sea-level change guidance. We developed new guidance on vertical control in collaboration with NOAA [26, 27]. USACE also updated existing guidance [24] on sea-level change to reflect best available science in collaboration with NOAA National Ocean Service and USGS, plus numerous external reviewers [28].

The USACE [28] sea-level guidance applies to engineering and planning for all USACE civil works projects within tidally influenced waters, including new and ongoing projects. The updated guidance takes a scenario approach with three plausible futures considered. USACE considered the IPCC [10] results as potentially too low to use alone for planning and design, despite the use of information obtained since 1987, since the IPCC results adopted a less sophisticated approach to the dynamics of ice discharge from polar ice caps and do not reproduce historical trends in sea level rise. USACE is currently working on follow-on guidance on sea-level change impacts, responses and adaptation (as identified in Table 21.1 above). The interagency team includes a representative of Reclamation's Mid-Pacific Regions as well as NOAA, USGS, Navy, FHWA, and international experts.

Reclamation does not have specific guidance on how to plan, design, or operate projects impacted by changing sea levels. However, the Reclamation Mid-Pacific Region in 2009 commissioned a review of existing procedures in the Sacramento-San Joaquin Delta area.[2] The review cited the USACE [28] guidance, IPCC [10], and sea-level change assessments conducted by California Department of Water Resources (CA DWR) and the CALFED Independent Science Board (CALFED ISB). Reclamation summarized the CALFED ISB position that IPCC 2007 should be considered as a minimum future condition, with upper bounds estimated using empirical modeling approaches such as Rahmstorf [18]. CALFED ISB noted numerical model weaknesses and limitations, and recommended that engineering design criteria address low-probability events. CADWR suggested a similar approach considering both global sea-level change and extreme events.

21.4 Summary

Given the magnitude of climate change impacts facing water resources managers in the United States, collaboration is essential. With similar but complementary mission areas, the two largest water resources management agencies in the U.S., USACE, and Reclamation, are working together to develop a consistent approach to climate change adaptation. Beginning with basin-wide studies in the western U.S. in 2006, an area particularly impacted by observed climate changes to snow-dominated watershed, they have partnered to address climate challenges by first identifying the issues, assessing user needs, and working to fill user needs as required for climate change adaptation. They joined with water resources science agencies to define the federal water resources management perspective, including user needs for improving tools and information supporting long-term planning and operations and assessing capabilities to use weather and climate forecasts in federal water resources management. They have explored the issue of nonstationary hydrology with respect to climate change through a workshop that will provide a basis for updated policies. They are also working with other water resources agencies to develop standardized methods to select decision-scale procedures from the sometimes overwhelming portfolio of climate information. Though much of the interagency collaboration centers on hydrology-related issues, the two agencies are also

[2] Levi D. Brekke, personal communication April 2010.

moving forward with guidance development for sea-level changes. USACE is committed to a consistent yet flexible national approach to climate change adaptation that recognizes the requirement to act now, and to adapt approaches based on new knowledge. We believe that this approach is one that can prove useful to others facing climate change adaptation challenges.

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Chapter 22
Mapping Sea Level from Space

Precision Orbit Determination and Satellite Altimetry

A. Salama, J. Willis, and M. Srinivasan

Abstract Since 1992, a series of satellite missions, beginning with TOPEX/Poseidon (T/P) and followed by Jason-1 and the Ocean Surface Topography Mission on Jason-2 (OSTM/Jason-2), have combined precision orbit determination (POD), a sophisticated method to determine precise height of spacecraft above the center of the Earth, and satellite altimetry to make precise measurements of sea surface height (SSH) and to map ocean surface topography.

These missions' unprecedented continuous 18-year-long record of SSH has revolutionized oceanography. With support provided by the National Aeronautics and Space Administration (NASA), the National Oceanographic and Atmospheric Administration (NOAA), and European partners (the French space agency, also known as the Centre National d'Etudes Spatiales (CNES), and the European Organisation for the Exploitation of Meteorological Satellites (Eumetsat)), these altimetry missions continue to help us understand the effects of the changing ocean on climate and provide significant benefits to society. Their measurements are being used to map SSH, geostrophic velocity, significant wave height, and wind speed over the global oceans.

Orbiting at a height of 1,336 km above Earth's surface, the satellites measure the SSH every 6 km along the ground track, with an accuracy of 3–4 cm, covering the global oceans every 10 days. These highly accurate measurements would not be possible without the ability to determine the satellite's exact position relative to the center of the Earth. This is achieved by using POD. Three of the five instruments on board the spacecraft provide critical satellite tracking information for POD. The NASA Laser Retroreflector Array (LRA) uses satellite laser ranging. The CNES

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Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) system uses Doppler radio data and a high-performance global positioning system (GPS) receiver that provides range, precise carrier phase, and timing signals. POD combines satellite tracking information with accurate models of the forces acting on the satellite (e.g., gravity, aerodynamic drag) that govern the satellite motion. This process provides the very-high-precision satellite orbital heights that, together with satellite altimetry, allow accurate estimation of SSH.

Data from these missions have proved to be a key to understanding Earth's delicate climate balance and are a critical component of global climate studies. They provide insight on short-term climate events, such as El Niño and La Niña, as well as longer-term climate events, such as the Pacific Decadal Oscillation (PDO). Altimeter data products are currently used by hundreds of researchers and operational users over the globe to monitor ocean circulation and improve our understanding of the role of the changing ocean in climate and weather.

The missions' measurement of rising sea level, a direct result of Earth's warming climate, are especially important for coastal communities and decision makers and might help save lives and property.

The legacy of satellite altimetry created by T/P, Jason-1, and OSTM/Jason-2 and the important data record they have collected are being continued. To ensure continuity with these missions, a group of nations and their science organizations plan to launch Jason-3 in 2013, Jason-CS/4 by 2017, and a next-generation Surface Water and Ocean Topography (SWOT) mission by end of the decade.

22.1 Introduction

More than two-thirds of Earth's surface is covered by the ocean; consequently, the ocean has a tremendous influence on global climate. The ocean distributes heat, salt, nutrients, and other chemicals around the world. Understanding ocean circulation is, therefore, vital to understanding climate change and other societal issues related to the oceans. From space, we can observe our vast ocean on a global scale and monitor critical changes in ocean currents and global sea level rise. From 1,336 km above the Earth, ocean altimetry satellites measure the sea surface height (SSH) to an accuracy of 2.5 cm, covering the global ocean every 10 days.

The National Aeronautics and Space Administration (NASA) launched the TOPEX/Poseidon (T/P) ocean altimeter mission in 1992 as a joint NASA/Centre National d'Etudes Spatiales (CNES) mission to study ocean circulation and its effects on climate. This mission was the beginning of a revolution in oceanography. Two follow-on missions, Jason-1 and the Ocean Surface Topography Mission on Jason-2 (OSTM/Jason-2), have extended the science data record of global SSH to almost 18 years. This suite of ocean altimetry missions has produced an uninterrupted time series that provides scientists with, among other things, critical information regarding an important climate change indicator: global sea level rise.

Rigorous cross calibration/validation (cal/val) among T/P, Jason-1, and OSTM/Jason-2 has ensured a consistent record across the missions, resulting in a unique global data set that allows scientists to address topics ranging from sea level rise to phytoplankton blooms, eddy generation, and iceberg detection.

Highly precise knowledge of the orbits of the spacecraft is required to achieve centimeter-accuracy measurements of SSH. The satellites are designed with redundant tracking systems that enable scientists to calculate the height of the spacecraft above the center of Earth very precisely using a technique called precision orbit determination (POD). POD is then combined with satellite altimetry, which measures the distance between the satellite and the ocean surface. The combination of these measurements allows researchers to map the hills and valleys of the ocean surface, or the ocean surface topography.

NASA, along with the National Oceanic and Atmospheric Administration (NOAA) and European partners, the French space agency, CNES, and the European Organisation for the Exploitation of Meteorological Satellites (Eumetsat), continue to advance oceanographic research through these missions, increasing our understanding of the effects of the ever-changing ocean on our climate. In addition to mapping ocean surface topography, these missions provide an unprecedented wealth of ocean data that is being used to map changes in geostrophic surface velocity, significant wave height, and wind speed over the global oceans.

Currently, Jason-1 and OSTM/Jason-2 are flying in a tandem configuration. The combined data from these two missions provides the enhanced resolution needed to track eddies, resolve small-scale structures in the mean flow, and improve understanding of ocean dynamics.

In addition to enabling fundamental progress in the science of oceanography and climate change, T/P, Jason-1, and OSTM/Jason-2 data have yielded many benefits to society. They are used routinely for ship navigation and safety, offshore operations, fisheries management, hurricane forecasting, river and lake level monitoring, and other applications. In their new tandem orbit, Jason-1 and OSTM/Jason-2 provide enhanced resolution for these and new applications, which will continue to benefit society and pave the way for new operational altimetry missions.

Over the past several years, an international initiative has been proposed to establish a Global Earth Observation System of Systems (GEOSS). One key component of this is a Global Ocean Observing System (GOOS). OSTM/Jason-2 and Jason-1 have become essential components of GOOS.

The measurement of ocean surface topography by satellite altimetry has been considered the most successful approach to observing global ocean circulation [1].

22.2 Combination of POD and Altimetry

POD is combined with satellite altimetry to map the hills and valleys of the ocean surface, or the ocean surface topography. The SSH determination is a two-step process. The first step is to characterize the precise height of the spacecraft above the center of the Earth using POD. The second step is to measure the range from the satellite to the ocean surface using altimetry. The altimetry measurements are subtracted from POD estimates of satellite orbital height above the center of the Earth, resulting in SSH. A more detailed account of these two steps is presented below, followed by an outline of how the changing ocean plays a major role in influencing changes in the world's climate and weather.

After its launch in December 2001, Jason-1 completed its cal/val phase in late 2002. Extensive comparative analysis of the data collected simultaneously from both Jason-1 and T/P during the first cross-calibration experiment for radar altimetry ensured a seamless transition of the measurement from T/P to Jason-1, thereby creating a continuous climate data record. This same process was implemented in the transition from Jason-1 to OSTM/Jason-2, resulting in an ongoing climate record of sea surface height that is nearing two decades in duration.

22.2.1 Precision Orbit Determination (POD)

Three of the five instruments on board the spacecraft provide the baseline tracking information for POD. The onboard NASA LRA serves as a target for 10–20 satellite laser ranging (SLR) stations that dot the Earth's surface. CNES's DORIS system provides an important additional set of tracking Doppler data and is anchored by approximately 50 ground-based beacons. NASA's GPS receiver provides precise, continuous tracking of the spacecraft by monitoring range, phase, and timing signals from 8 to 12 GPS spacecraft at the same time. The data obtained from the SLR stations, the DORIS measurements, and GPS continuous tracking are collected over an orbital arc of 10 days during which the spacecraft cover the global oceans in a repeat cycle. This significant amount of data is filtered in a sophisticated process to remove data that does not meet certain requirements. The output of this process is an array of essential observables (O) that, when combined with calculated positions of the spacecraft (C), provide the high-precision ephemeris. The C values are obtained using very accurate models of the forces that govern the satellite motion (e.g., gravity, aerodynamic drag). To produce accurate estimates of the satellite orbital height, POD uses a sophisticated estimation technique to minimize the difference between the O and C values. This process, in the end, supports an orbital data accuracy of 1–2 cm (RMS) for the radial component. Figure 22.1 shows the POD tracking elements.

22.2.2 Satellite Altimetry

The altimeter onboard the satellite provides the range measurement; that is, the distance to the ocean surface from the satellite. The SSH measurement is derived through a calculation of the range measurement and the POD. Every 10 days, as

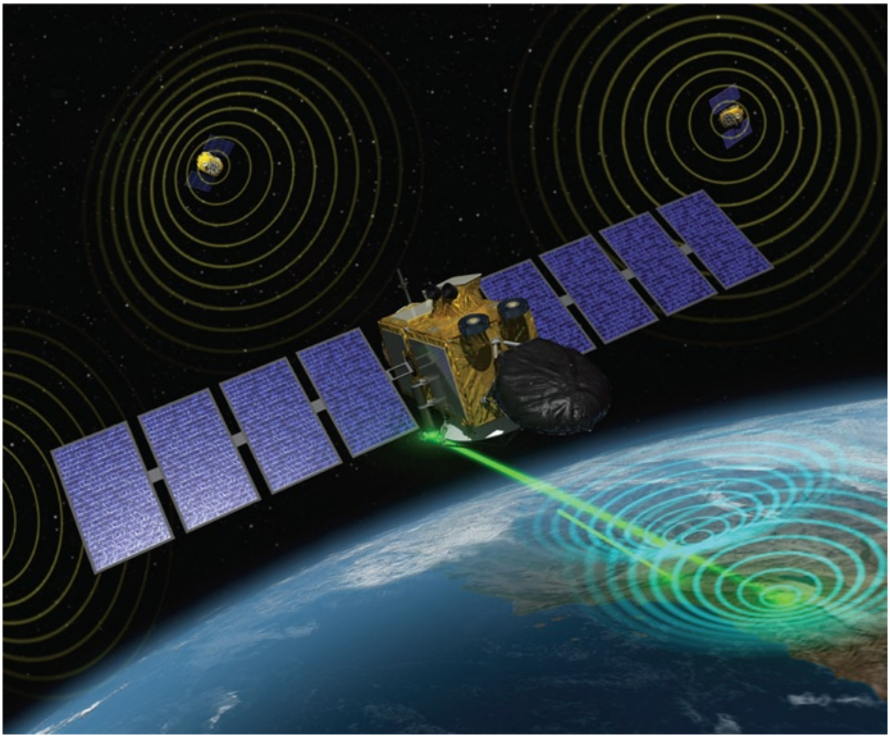

Fig. 22.1 Baseline tracking elements of Precision Orbit Determination: the laser retroreflector array (*LRA*), DORIS ground beacons, and GPS satellites

Jason-1 and OSTM/Jason-2 complete 127 revolutions, or orbits, around the Earth, the satellites' radar altimeters measure the height of more than 90% of the world's ice-free ocean.

22.2.3 Measurement Systems

Soon after the success of Sputnik, it became apparent that it was feasible to fly a radar altimeter onboard an orbiting artificial satellite for global measurement of the shape of sea surface. The challenge was the required measurement accuracy. After two decades of effort toward improvement [2], T/P was the first satellite altimetry mission that was capable of meeting the required accuracy for measuring the subtle changes in ocean surface topography caused by the massive movement of ocean water. The general measurement system of these satellites is illustrated in Fig. 22.2.

Figure 22.3 shows the range of ocean surface topography measurements. An animation of how the measurement systems work as the satellite orbits the Earth can be found at: http://sealevel.jpl.nasa.gov/gallery/OSTM-jason2-inst-movies.html [3].

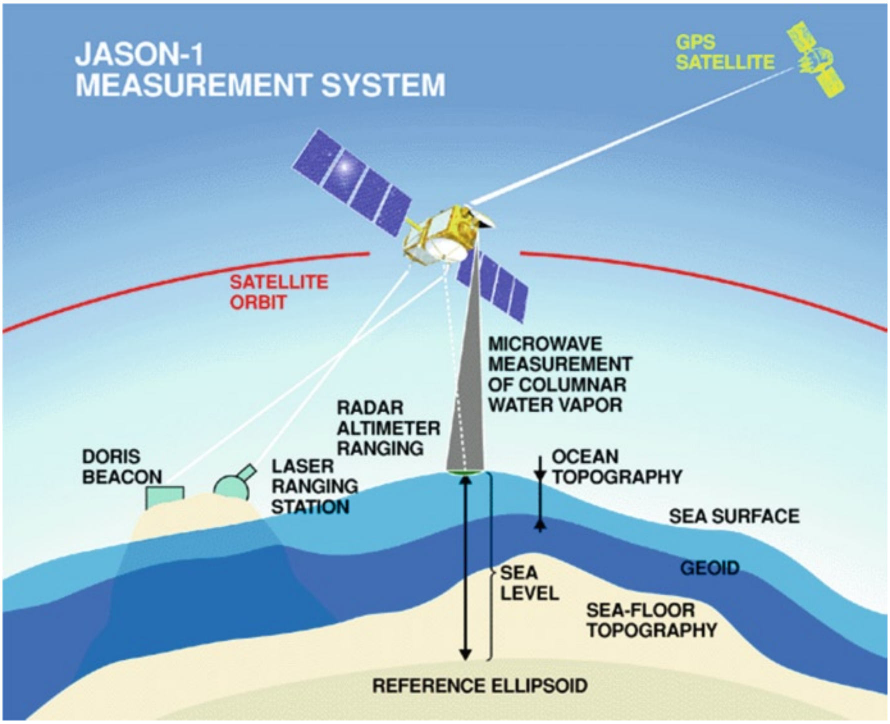

Fig. 22.2 The Jason-1 measurement systems. POD base tracking systems include the GPS satellite system, DORIS beacons, and laser ranging stations

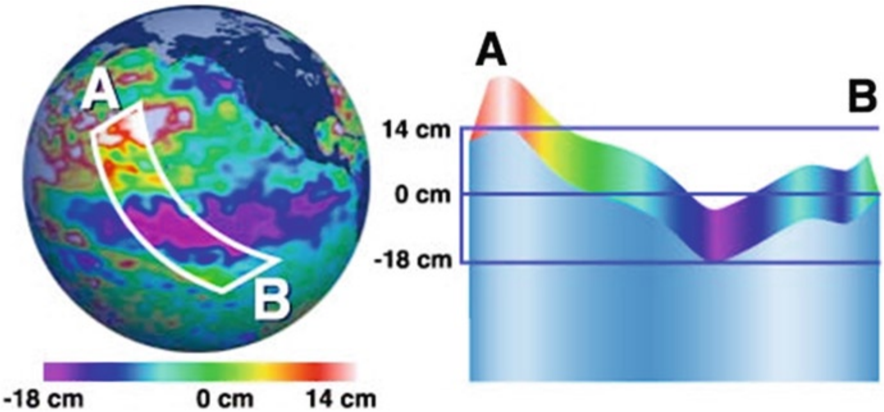

Fig. 22.3 The range of ocean surface topography measurements

The primary measurement instrument is a dual-frequency radar altimeter for making range measurements; that is, measuring the distance from the spacecraft, whose position is known from POD, to the sea surface. A microwave radiometer is used to make corrections for errors caused by water vapor in the atmosphere.

In addition to SSH, the instruments also provide measurements of the height of large ocean waves, the speed of ocean surface winds, and estimates of other atmospheric parameters (total electron content and water vapor).

Many factors contribute to SSH, including gravity, tides, and ocean currents. For example, over the globe, gravity changes SSH by tens of meters. On the other hand, ocean currents alter SSH by only a few centimeters. Conversely, although gravity's influence on SSH is relatively stable, tides, currents, and global sea-level rise change SSH constantly. Improved knowledge of SSH and the factors that contribute to it helps us track important changes in ocean circulation and its role in the global climate system.

22.3 Climate Research at NASA

Part of NASA's mission is to develop an understanding of the total Earth system and the effects of natural and human-induced changes on the global environment. Our ocean plays a major role in influencing changes in the world's climate and weather. Collecting and analyzing long-term ocean data from satellites makes it possible to understand the ocean in a relevant context for scientific and societal gains.

Using satellite data and computer models, scientists investigate how the oceans affect the evolution of weather, hurricanes, and climate. The ocean stores the heat that fuels hurricanes and patterns of warming and cooling, like El Niño and the Pacific Decadal Oscillation (PDO). Ocean heat also influences weather and rainfall across the globe. In addition, the ocean stores more than 80% of the excess heat trapped by anthropogenic greenhouse gasses [4]. Short-term weather patterns influence personal, economic, and agricultural decisions on a daily and seasonal basis. Long-term weather patterns influence the water supply, food supply, trade shipments, and property values [5].

Satellite altimeter missions like those highlighted in this chapter allow us to better understand the dynamics of the ocean and provide relevant information to address society's needs. By providing ongoing observations of small-scale ocean features in addition to sea level rise and large-scale changes in ocean circulation, Jason-1 and OSTM/Jason-2 are addressing ocean and climate aspects of an overarching NASA Earth science focus: How is Earth changing? What are the causes? What are the consequences for life on Earth?

22.3.1 Science Objectives

More than 17 years of scientific discovery has broadened the science objectives of NASA's ocean altimetry missions. The science goals are to:

- Measure global sea-height change and provide a continuous view of changing global ocean surface topography.

- Calculate the transport of heat, water mass, nutrients, and salt by the ocean.
- Increase our understanding of ocean circulation and seasonal changes and how the general ocean circulation changes through time.
- Provide estimates of significant wave height and wind speeds over the ocean.
- Test how we compute ocean circulation caused by winds.
- Improve the knowledge of ocean tides and develop open-ocean tide models.
- Improve forecasting of climatic events like El Niño and of global climate in general.
- Describe the nature of ocean dynamics and develop a global view of the Earth's ocean.
- Monitor the variation of global mean sea level and its relation to global climate change.
- Improve our understanding of recently discovered zonal jet-like features in the global ocean circulation.

22.3.2 Climate Studies

The data from the missions described in this chapter have proved to be a key to understanding Earth's delicate climate balance and are a critical component of global climate studies. The missions are used for research on short-term climate events such as El Niño and La Niña, as well as long-term climate events such as the PDO. Hundreds of researchers and operational users around the globe currently use altimeter data products to monitor ocean circulation and improve our understanding of the role of the ocean in climate and weather.

Satellite observations of our oceans over the past three decades (in particular, data from satellite altimeters on T/P and the Jason missions) have truly revolutionized our understanding of climate change through global measurements and modeling of the ocean-atmosphere climate system. The availability of global ocean surface topography data on time scales of days to years to decades is a vital resource for scientists and policy makers in fields such as oceanography, meteorology, ocean commerce, and disaster mitigation [6].

Data and imagery from these missions are being used in a number of climate-relevant applications. By modeling changes in the distribution of heat in the ocean with altimetry data, scientists can study climate impacts of ocean warming.

22.3.2.1 Sea Level Rise

Earth's warming climate is resulting in a steady rise in global mean sea level. Anthropogenic greenhouse gasses trap extra heat from the Sun. The vast majority of this heat is stored in the ocean. The warming waters expand as they heat up, causing a third to a half of global sea level rise [7]. The remainder is due to ice loss from glaciers and ice sheets, which are also sensitive bellwethers of a warming climate.

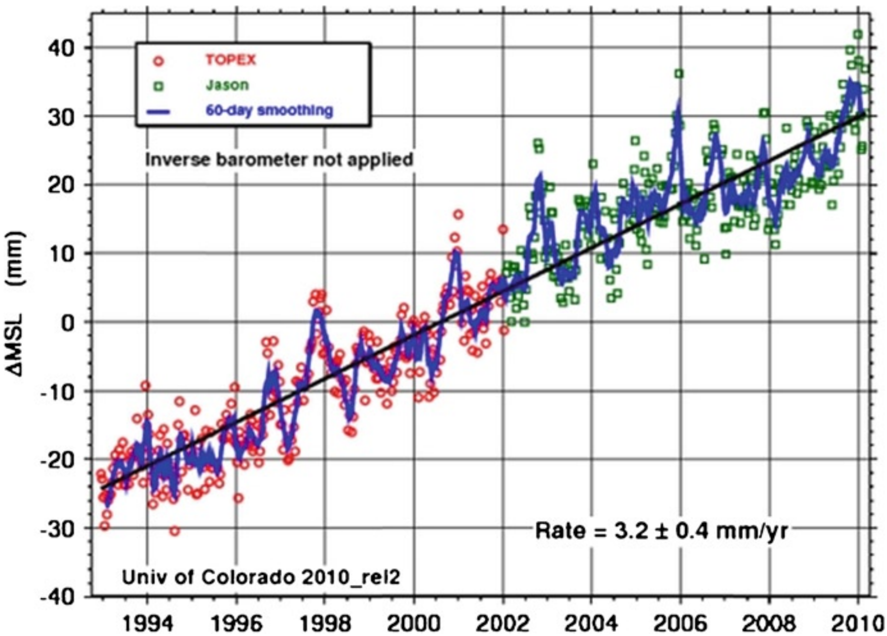

Fig. 22.4 Mean sea level change as measured by TOPEX/Poseidon, Jason-1, and OSTM/Jason-2. Credit: University of Colorado

Long-term mean sea level change, therefore, provides an important measure of human influence on the global climate. Measuring such changes not only provides evidence of human-induced change, it also provides an important test for coupled climate model predictions. Over the last century, global sea level change has typically been estimated from tide gauge measurements. However, satellite altimeter measurements combined with precisely known spacecraft orbits (from POD) now provide a dramatically improved measurement of global sea level change (Figs. 22.4 and 22.5).

Since August 1992 the satellite altimeters have been measuring sea level on a global basis with unprecedented accuracy. The T/P satellite mission provided observations of sea level change from 1992 until 2005 [8].

By monitoring changes in SSH, these missions provide an opportunity for coastal communities and decision makers to respond to change, potentially saving property and lives.

Warming water and melting land ice have raised global mean sea level 4.5 cm (1.7 in.) from 1993 to 2008. This rise is, however, by no means uniform. Figure 22.5 shows the average rate of sea level change between 1993 and 2008 based on data from the T/P and Jason-1 satellites. Light blue indicates areas in which sea level has remained relatively constant since 1993. Red and orange are regions where sea levels have risen the most rapidly—up to 12 mm per year—and that contain the most heat.

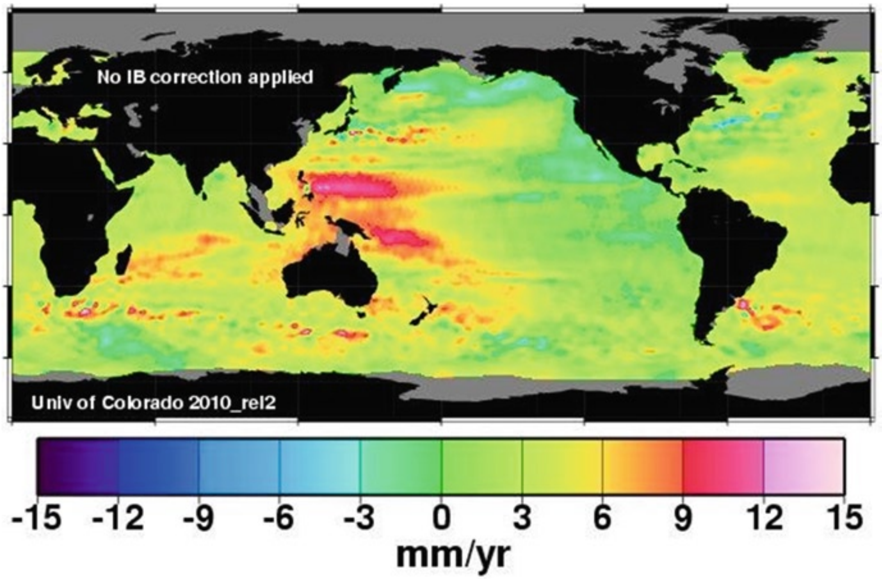

Fig. 22.5 The trend of global sea level rise from 1993 to 2008 [8]

Blue areas show where sea levels have dropped, due to cooler water. Many of these patterns reflect natural fluctuations in currents and the storage of heat in the ocean.

22.3.2.2 Tropical Cyclone Research

Tropical cyclones, also known as hurricanes, are characterized by very high waves and strong winds that can be measured by altimeters [9]. Altimeter data are being incorporated into complex atmospheric models that are used to both predict hurricane season severity and forecast individual storm intensity.

Near-real time satellite altimetry and surface temperature data are being used to improve hurricane and cyclone predictions. These events can increase their intensity and change direction as they pass over regions of high heat content in ocean waters. These areas of higher heat content are well-defined in the SSH data. As a cyclone or hurricane passes over a warm eddy in the ocean, the strong wind mixing penetrates into underlying warmer water and the hurricane can intensify [10].

22.3.2.3 El Nino and La Nina and the PDO

"El Niño" refers to anomalously warm water in the central and Eastern Pacific Ocean, typically during late summer and early winter months. El Niño events typically occur every 3–7 years and disrupt fisheries, shift rainfall patterns, and have been associated with severe weather events worldwide. "La Niña" refers to cold-water conditions off the western tropical coasts of the Americas, occurring irregularly and occasionally following El Niño conditions. Impacts include regenerated fisheries in some regions, drought in the central and eastern Pacific, and rain in the western Pacific. The PDO is a longer-term climate event (on the order of 10–30 years) that is reflected in characteristic cooler and warmer regions of the Pacific Ocean. Ocean altimetry missions provide an important extended time series for monitoring these 3–7-year events.

22.3.2.4 Monitoring Rivers and Lakes

Altimeter data are also used to monitor the water level of rivers and lakes of the world. The data are especially useful in remote regions where in-situ observations are difficult. More advanced studies are now combining the data with other remote sensing observations, modeling tools, and theoretical knowledge that will lead to (a) the development of flood and drought warning indicators and (b) the provision of higher-level products, such as river discharge and storage volume data.

22.4 A Legacy of Science

Despite the major advances brought about by satellite altimeter observations, predicting future sea level rise remains extremely difficult. Unlike projections of atmospheric CO_2 increase and global temperature increase, which have been predicted relatively accurately, projections of sea level rise based on coupled climate models have typically been conservative.

Sea level projections from the Third Assessment Report of the IPCC (2001), for instance, significantly underestimated the rate of sea level rise over the past two decades (Fig. 22.6). The Fourth IPCC Assessment Report [7] placed no upper bound on sea level rise projections for the twenty-first Century [11]. Much of this uncertainty arises from a lack of knowledge concerning the response of glaciers and ice sheets to the warming climate. Such uncertainty underscores the critical need for continued observations of global sea level with accuracy that can only be achieved by precise satellite observations, such as those from T/P, Jason-1, and OSTM/Jason-2 and future Jason-class satellite altimeter missions.

22.4.1 Future Missions

Plans are underway to extend the legacy of satellite altimetry missions into the future (see Fig. 22.7). With the launch and successful cross-calibration of OSTM/Jason-2, the accurate climate record of ocean surface topography is expected to be extended to the first operational mission, Jason-3, which is currently being planned

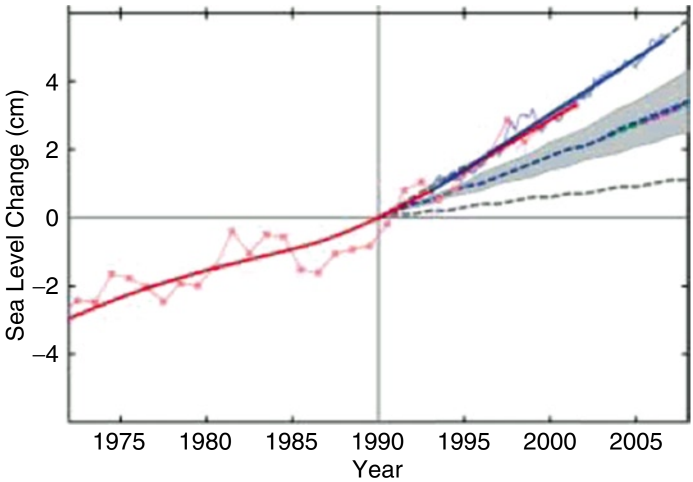

Fig. 22.6 Changes in sea level since 1973, compared with the scenarios of the IPCC Third Assessment Report (shown as *dashed lines* and *gray* ranges). Sea-level data based primarily on tide gauges (annual, *red*) and from satellite altimeter (3-month data spacing, *blue*, up to mid-2006) and their trends [11]

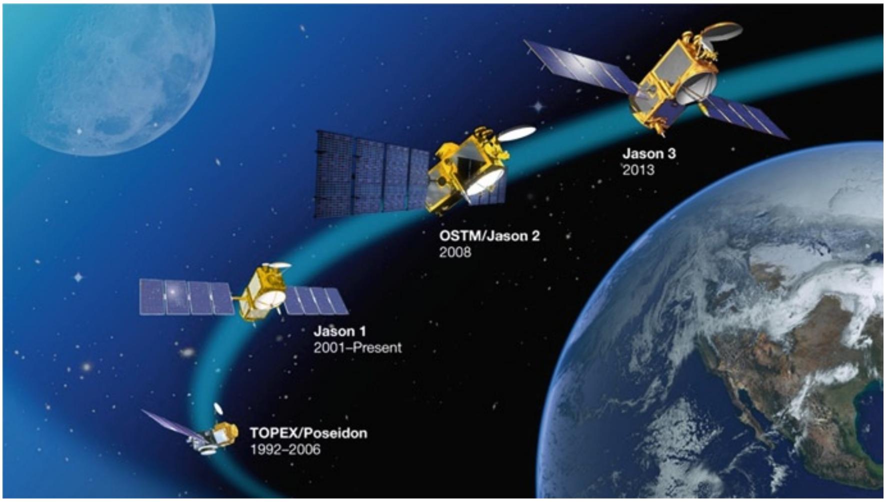

Fig. 22.7 The legacy and future of U.S.-European partner ocean altimetry missions

by NOAA and Eumetsat. This mission will ensure data and science continuity and will to continue to provide numerous benefits to society. The U.S., along with our European partners, plans to launch Jason-3 in 2013. They subsequently plan to develop and launch the Jason-CS/4 mission by 2017. In addition, NASA and CNES are working together to propose a next-generation, wide-swath altimetry mission called the Surface Water and Ocean Topography (SWOT) mission, to launch in 2019.

NASA and its partners will extend the global sea level record into the 2010s and eventually turn over this key climate data record to operational agencies to be maintained indefinitely.

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Chapter 23
Integrated Modeling to Mitigate Climate Change Risk Due to Sea Level Rise

Imperiled Shorebirds on Florida Coastal Military Installations

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Abstract Climate change is expected to significantly alter low-lying coastal and intertidal areas, which provide significant seasonal habitats for a variety of shoreline-dependent organisms. Many coastal military installations in Florida have significant coastal habitats and shoreline-dependent bird data strongly illustrate their seasonal importance for birds. Potential land use changes and population increases, coupled with uncertain predictions for sea level rise, storm frequency, and intensity have created a significant planning challenge for natural resource managers. This paper provides a framework to integrate multiscale climate, land cover, land use, and ecosystem information into a systematic tool to explore climate variability and change effects on habitat and population dynamics for the state-threatened residential Snowy Plover, and the migratory Piping Plover and Red Knot, on selected coastal Florida military sites in Northwest Florida. A proof-of-concept study is described that includes climate data, species distribution and a coastal wetland land cover model coupled with global sensitivity/uncertainty analysis methods. The results of these integrated models are used to explore habitat dynamics and management options within an uncertain world.

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23.1 Introduction

Climate change (via sea level rise and altered weather patterns) is expected to significantly affect low-lying coastal and intertidal areas, which provide seasonal habitats for a variety of shoreline-dependent organisms. It is now recognized that considering the effects of climate on natural resources is an issue of concern globally. At the national level, Florida has been identified as one of the states most vulnerable to climatic impacts [16, 56]. Recent projections of habitat loss for shoreline-dependent birds at selected coastal sites in the U.S. range between 20% and 70% loss [29]. This is particularly worrisome for shoreline-dependent species such as the Snowy Plover (*Charadrius alexandrinus nivosus*), the Piping Plover (*Charadrius melodus*), and the Red Knot (*Calidris canutus*) that are experiencing significant habitat loss and increasing human disturbance in breeding/nesting, brood-rearing, wintering, and migratory-stopover areas [32]. The Florida Fish and Wildlife Conservation Commission (FWC) lists Snowy Plovers as threatened, the U.S. Shorebird Conservation Plan lists them as Extremely High Priority for conservation [12], and an unresolved petition has been filed to add Gulf Coast Snowy Plovers as a candidate to the U.S. Fish and Wildlife Service's (USFWS) list of threatened and endangered wildlife [51]. In addition to Snowy Plovers, federally listed Piping Plovers occur in high numbers (relative to the rest of their non-breeding range) on Florida's barrier islands during the non-breeding season. Piping Plovers are listed by the USFWS as three separate sub-populations: the Great Plains and Atlantic Coast populations are listed as threatened and the Great Lakes population is listed as endangered [76, 77]. Color-banded individuals from all three populations have been observed during fall migration and winter in Florida [75, 77]. Red Knot populations have declined dramatically during the past decade and likely will be federally listed in the near future. As sea level rises, coastlines will likely move inland and much of the coastal shoreline will be water against seawalls with little or no beach, dune, and intertidal habitats that are critical to shoreline-dependent bird ecology. Shoreline-dependent organisms will increasingly rely on habitats provided on federal lands where beaches will be able to slowly migrate inland with little constraint. Here we propose an integrated modeling framework for assessing the sea level rise effects due to climate change on shoreline infrastructures and shoreline-dependent birds (Fig. 23.1).

Coastal military installations in the southeastern U.S., such as Eglin Air Force Base (AFB), Tyndall AFB, Pensacola Naval Air Station, Cape Canaveral Air Force Station, and Camp Lejeune Marine Corps Base, all have significant coastal habitats and shoreline-dependent bird data to suggest their seasonal importance for birds. Recent work by American Bird Conservancy clearly shows the importance of Department of Defense (DoD) and National Park Service (NPS) lands to the breeding Snowy Plover and wintering Piping Plover (Fig. 23.2). Eglin AFB and Tyndall AFB, along with State Park and NPS shorelines, accounted for 80% of all estimated nesting Snowy Plover pairs in the Florida Panhandle during recent statewide surveys. Tyndall AFB had the highest counts for wintering Snowy Plovers of anywhere in the state [51].

In coastal military installations, there is also the need to make sure that coastal areas remain intact and viable for training (e.g., amphibious landings). For example,

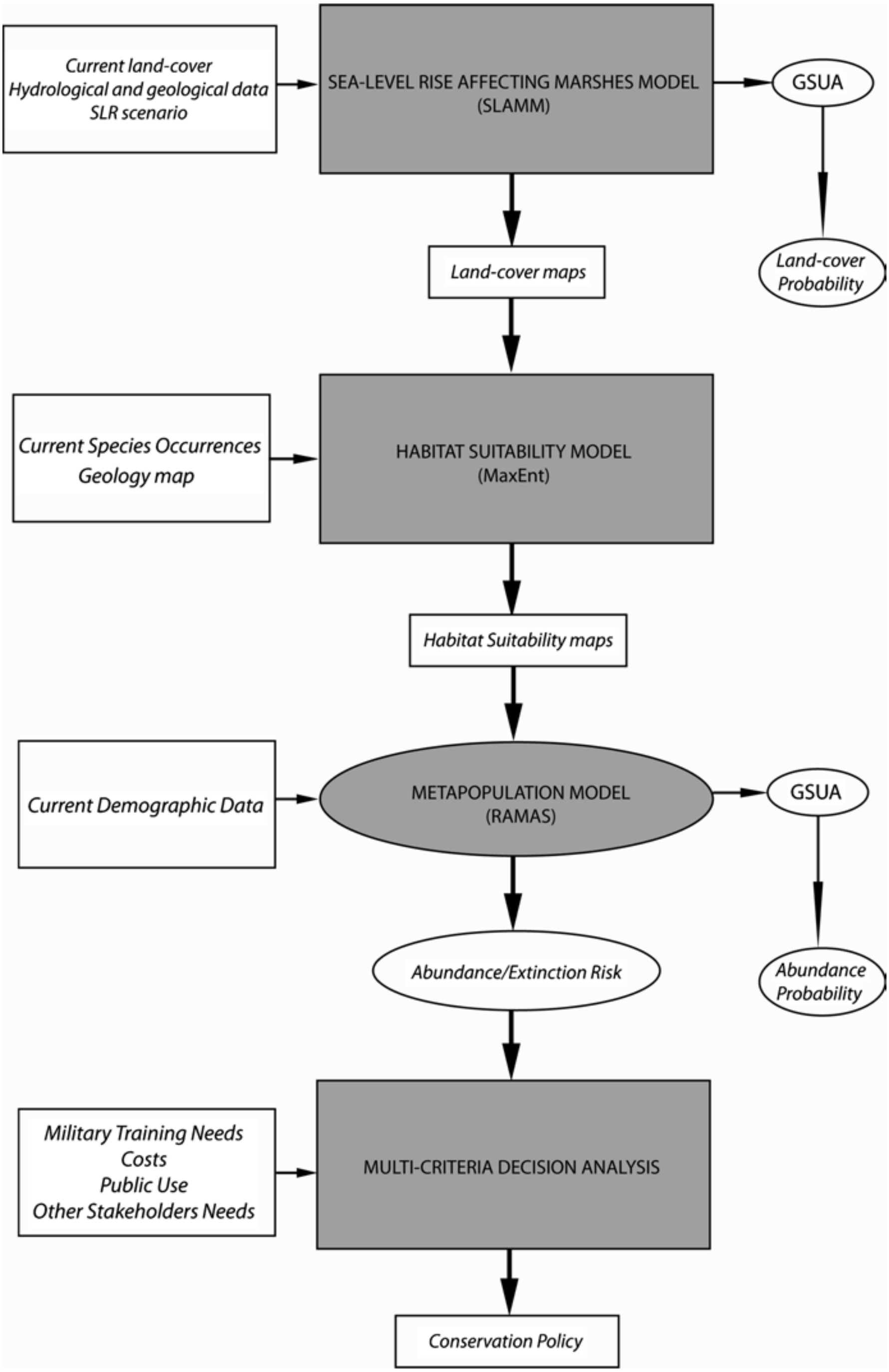

Fig. 23.1 Integrated Modeling Framework. The square nodes are deterministic nodes; the circle nodes are stochastic nodes

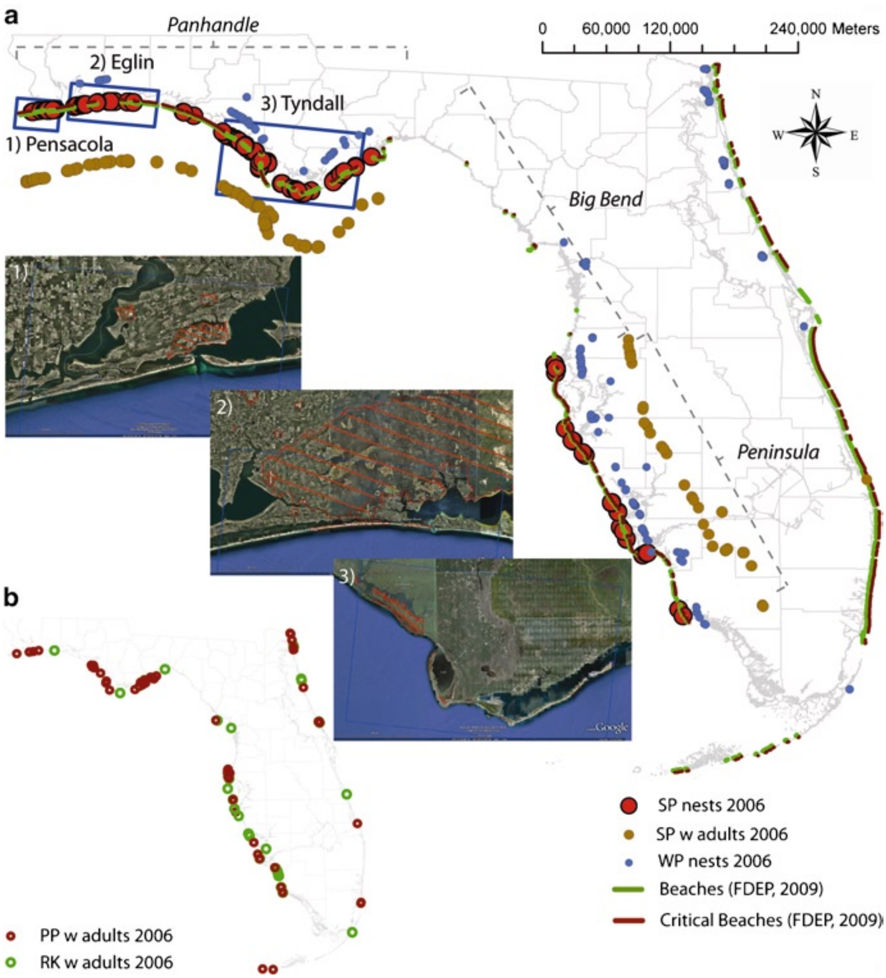

Fig. 23.2 Snowy plover distribution. (**a**) Snowy plover distribution in the 2006 breeding and wintering season. (**1**), (**2**), and (**3**), are the satellite images of the DoD installations involved in the project (Pensacola NAS, Eglin AFB, and Tyndall AFB). (**b**) Piping plover and red knot wintering distribution [20]

barrier island habitat on Eglin AFB is currently being assessed for future projects (e.g., access road armoring, dune and shoreline renourishment, creation of seawalls and bulkheads) to help support missions (Bruce Hagadorn, Chief, Natural Resources Branch, Eglin AFB, Pers. Communication). Recent DoD-focused threatened, endangered, and at-risk species (TER-S) research and management objectives have stressed the need for greater systems understanding and tool development at a variety of spatial and temporal scales [72]. Together these factors produce a critical need for land and facility managers to act in the face of uncertain outcomes and to balance multiple, potentially-conflicting objectives with their decisions. This need presents a daunting technical challenge to develop a practical and understandable mechanism for the propagation of uncertainty through climate change scenarios and habitat and TER-S population models into a toolset for managers to weigh all available evidence in their decisions. The use of adaptive management [34] and decision analysis methodologies [30] may be useful to achieve the alignment of scenarios and data with the ecological, financial, and military objectives of each site.

The objective of this paper is to propose and test an adaptive management/decision analysis framework that integrates multiscale climate, land use, and ecosystem information into a systematic toolset (Fig. 23.1) to explore how climate variability and change effects may affect habitat and population dynamics for Snowy Plover on selected coastal Florida military sites in northwest Florida (Eglin AFB, Tyndall AFB, and Pensacola Naval Air Station). Accordingly, this paper is divided into a methodology section that highlights techniques and a section containing proof-of-concept results. The final section provides a discussion of the early lessons and questions explored in the analysis.

23.2 Background Information and Data

23.2.1 Review of Framework Concepts and Method

This section provides a brief review of the tool systems and databases that support the integrated assessment framework including discussion of climatic databases and downscaling, land use and wetland databases, habitat modeling, and metapopulation modeling (Fig. 23.1). Additionally, a review of uncertainty and sensitivity analysis as well as decision analysis is provided.

The resulting management tool integrates four components: (A) multiscale climate data including historical and projected conditions, (B) habitat and population models for risk assessment, (C) sensitivity/uncertainty analysis methods, and (D) multicriteria decision analysis (MCDA). Figure 23.1 shows a conceptual model of the various forces affecting TER-S on Florida bases. A variety of forces (represented by their information and data) have influence upon TER-S populations and their associated habitat. All these factors have varying levels of uncertainty and variation in their representation as well as their actual influence upon the TER-S. The models that are created to simulate these populations add an additional level of uncertainty to the predicted scenarios that managers request. As a result, two situations tend to arise from most modeling studies. The multiple and highly uncertain predictions are less useful to decision makers than they expect so they disregard all results in favor of a more subjective approach, or a small subset of the predictions are selected because they are generally acceptable in terms of integrating with other information. In both cases, information is often disregarded in the move towards a practical management decision. The initial proof-of-concept system was used to explore one selected species, Snowy Plover, that is a residential shorebird in Florida.

Further research efforts can build upon these tools and re-parameterize for additional species. Most significantly, the framework provides a systematic database-to-model-to-decision framework that embraces uncertainty/sensitivity issues within uncertain potential environmental conditions. Incorporation of uncertainty issues within adaptive management challenges demands an organized and methodical toolset that can help to parse through the often disparate and complex data. Recently developed tools include global sensitivity/uncertainty analysis methods [55, 69] and integration/decision analysis tools [41, 42, 48]. The use of MCDA methods allows all model-derived information to be integrated with existing management metrics for both single-project and adaptive management decision making.

23.2.2 Sea Level Rise Scenarios

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change projected future global sea level rise between 0.18 and 0.59 m by the year 2100 (0.18–0.38 m for the lowest emission scenario and 0.26–0.59 m for the highest emission scenario) [38]. However, there is now a general scientific consensus that these estimates are conservative [31, 59, 63]. The IPCC estimates thus provide only the lower limit for this study. In this work global sea level rise projections will be made for each Atmosphere-Ocean General Circulation Model (AOGCM) and emission scenario using the semi-empirical method developed by Rahmstorf [66]. The semi-empirical method projects global sea level rise using global mean surface temperature, a readily available output from AOGCMs. Using this method, Horton et al. [37] projected sea level rise between 0.47 and 1.00 m using AOGCM output from the CMIP3 dataset. While caution is required in extrapolating the relationship of Rahmstorf [66] beyond the data used to derive it, these results are generally consistent with other studies [31, 63].

Local sea level rise is caused by the combined effects of global sea level rise and location-specific factors such as land subsidence/rebound and elevation changes due to atmospheric effects. Local projections of sea level rise are calculated by removing the historical simulated global trend from local tide gauge records. In the land cover model we divided the Florida Gulf coast into seven areas in which the accretion, sedimentation, and erosion data are different [15]. The global trend will then be superimposed onto the residuals of the local trend, providing the local projection of sea level rise.

23.2.3 Storm Frequency and Intensity

There is currently no consensus on the effect that increased sea surface temperatures in the tropical Atlantic and Caribbean will have on the frequency and intensity of tropical storms that strike the southeast U.S. [27]. While there is a wide variation of results, there appears to be a tendency for a reduction in the frequency of storms due to an increased vertical wind shear [78] but an increase in their intensity [9, 27]. While several past studies have based their results on changes in the historical record (e.g., Mann and Emanuel [52]), convincing evidence has been made for systematic undercounts in the National Oceanographic and Atmospheric Administration (NOAA) HURDAT dataset prior to the satellite era [44] as well as an intensity bias in the historical record [47]. While these biases are believed to be now corrected, they serve to illustrate the uncertainty that has existed (and could potentially still exist) in historical observations.

While the future frequency and uncertainty of future tropical storms is uncertain, the direct effect that sea level rise will have on storm surge is relatively straightforward. Local projections of storm surge associated with tropical storms can be made by superimposing future local sea level rise onto hourly historical tide data. However, this approach does not address possible changes in storm frequency or intensity. Convertino et al. [21], analyzed the effect of tropical cyclones on the breeding distribution of Snowy Plovers, finding a positive interannual feedback among nesting ground probability and tropical cyclone events. Tropical cyclones shape the beach ecosystem in a way that is favorable for Snowy Plover (e.g., expanding the beach flat areas and creating ephemeral pools). This potentially enhances the abundance of Snowy Plover. The result is useful in metapopulation models that often assume the catastrophic influence of cyclones on every species.

23.2.4 Land Use, Land Cover, and Species Occurrence

The integrated framework described in Fig. 23.1 utilizes both state and national land cover, habitat, topography and species information as input factors for models and sensitivity/uncertainty analysis. Each of these datasets have inherent scale- and error-attributes that may affect model output variance.

23.2.4.1 Population and Land Use Changes

The Florida Geographic Data Library [28], located at the University of Florida's GeoPlan Center, is a virtual center for distributing spatial (GIS) data throughout the state of Florida (http://www.fgdl.org). The FGDL holds over 350 current and historic GIS layers from over 35 local, state, federal, and private agencies, including data on land use/ land cover, hydrography, soils, transportation, boundaries, environmental quality, conservation, and census, among others. Specific land use changes over the future have been derived from population and land use projections in the Florida 2060 report [81]. These datasets cover 20 year time steps, including 2020, 2040, and 2060. The land use information has been useful to mask the areas in the land cover map that will be considered developed in the future.

23.2.4.2 Wetlands and Elevation

The National Wetlands Inventory (NWI) of the USFWS [22, 58] classifies the State of Florida into land cover classes. The wetland classification from NWI is used to derive the model inputs for habitat change models. For the habitat suitability study [17, 18], the NWI map has been reduced to resolutions of 30 and 120 m to analyze the effect of the resolution on the predicted probability of occurrence of birds. Several sets of elevation data at different scales are available for the habitat suitability and change modeling. The elevation was derived from the U.S. Geological Survey (USGS) at resolution 30×30 m.

23.2.4.3 Shorebird Population and Nesting Information

Data of shorebird distribution and abundance are available during two different survey periods: (1) pre-hurricane, and (2) post-hurricane. Pre-hurricane maps include bird survey data from January 2001 (for non-breeding Piping Plovers, Red Knots, and Snowy Plovers) or February-August 2002 (nesting Snowy Plovers). Post-hurricane maps include bird survey data from January 2006 (for non-breeding Piping Plovers, Red Knots, and Snowy Plovers) or February-August 2006 (nesting Snowy Plovers). The distribution of shorebirds is along the North Coast of Florida (Panhandle region) and along the Gulf Coast. Migratory Piping Plovers and Red Knots are found also along the Atlantic coasts. Snowy Plovers reside in Florida the whole year while other shorebirds present a migratory behavior. GIS layers for 2001 and 2006 International Piping Plover Census (IPPC) counts were acquired directly from the USFWS Panama City Field Office, which coordinated the collection of these data in Florida. Data from IPPC are wintering data. Nesting data are from the Florida U.S. Fish and Wildlife Conservancy. Presences are also available for other migratory birds such as Least Terns, Black Skimmers, and American Oystercatchers, but the focus of the project is mainly Plovers. Occurrence maps for Snowy Plovers are also available for the 2008, 2009, and 2010 nesting seasons [65]. Snowy Plover behavior differs between summer (breeding and nesting period) and winter. Particularly, Snowy Plover tend to roost and forage in larger congregations during the winter months, so observations during the winter may not be indicative of population densities during the breeding season. We consider then only nesting data (More information can be found in Lott et al. [49, 50] and Himes et al. [36]).

23.3 Models and Methods

23.3.1 Habitat Modeling with the Sea Level Affecting Marsh Model (SLAMM)

The SLAMM (Sea Level Affecting Marshes Model) (Warren Pinnacle Consulting, Inc., Warren, VT), was originally developed in the 1980s with Environmental Protection Agency (EPA) funding. The model has been used to simulate changes in coastal habitats due to sea level rise in order to assess potential changes to numerous wetland areas [29, 45, 46, 57, 60, 61]. SLAMM is a raster (square, cell-based) land cover model that divides a simulated domain into discrete cells. The model simulates spatial changes to the 23 NWI wetland categories based on the dominant processes involved in coastal wetland conversions and shoreline modifications during long-term sea level rise including inundation (i.e., reduction in elevation due to sea level rise), erosion, overwash, saturation, and accretion. Each wetland class is associated with particular elevations and environmental conditions (e.g., salinity, tidal ranges) required for that specific wetland type to persist. Site-specific GIS data is required for simulations inclusive of digital elevation maps, land cover (NWI wetland types), sea level rise projections, and site-specific tidal range and storm intensity. SLAMM provides output in the form of GIS maps presenting the projected land cover, and tabular information displaying the proportions of wetland area change. Data for SLAMM simulations was obtained from different databases provided by governmental organizations such as NOAA, USGS, and NWI. SLAMM modeling predicts changes in Snowy Plover habitats under different climate change scenarios. The SLAMM result is then evaluated together with the result from the plover model presented below to identify essential nesting, feeding, and migration areas for the plovers. However, SLAMM can work also for different land cover models. Convertino et al. [17, 18], showed that the NWI is out-of-date for studying the distribution of the Snowy Plover in Florida. For this project, the 2006 land cover has been used and converted into SLAMM classes.

23.3.2 Maximum Entropy Principle for Species Distribution Prediction (MAXENT)

In order to derive habitat suitability maps that describe the probability of occurrence of birds, different species distribution models (SDMs) have been used [17, 18]. SDMs are numerical tools that combine observations of species occurrence or abundance with environmental layers [26]. They are used to gain ecological and evolutionary insights and to predict distributions across landscapes, sometimes requiring extrapolation in space and time. SDMs are now widely used across terrestrial, freshwater, and marine realms [26]. There is currently a strong debate in the scientific community about the comparison of many different niche-based SDMs [26, 62], and in comparing these niche-deductive-based models with mechanistic dispersal-based or niche-based models [11, 33]. The predictive habitat suitability models used are MaxEnt [64] and GARP [74], the latter through the openModeller platform [24]. Therefore the study focused also on the comparison with other possible methods.

The distribution computed by MaxEnt is the one that has maximum entropy among those satisfying the constraints that the expectation of each feature matches its empirical average. This distribution, without regularization, can be proved to be the same as the Gibbs distribution that maximizes the product of the probabilities of the sample locations, where a Gibbs distribution takes the form:

$$P(X) = \exp(c_1 * f_1(X) + c_2 * f_2(X) + c_3 * f_3(X)...) / Z \quad (1)$$

Here c_1, c_2, … are constants, f_1, f_2, … are the features, and Z is a scaling constant that ensures that P sums to 1 over all grid cells. The algorithm that is implemented by this program is guaranteed to converge to values of c_1, c_2, …, that give the (unique) optimum distribution P.

For each species, the program starts with a uniform distribution, and performs a number of iterations, each of which increases the probability of the sample locations for the species. The probability is displayed in terms of *gain*, which is the log of the number of grid cells minus the log loss (average of the negative log probabilities of the sample locations). The gain starts at zero (the gain of the uniform distribution), and increases as the program increases the probabilities of the sample locations. The gain increases iteration by iteration, until the change from one iteration to the next falls below the convergence threshold, or until maximum iterations have been performed.In the regularized case, the gain is lower by an additional term, which is the weighted sum of the absolute values of c_1, c_2, … . This limits overfitting and prevents c_1, c_2, … from becoming arbitrarily large. Minimizing the regularized loss (or equivalently, maximizing the regularized gain) corresponds to maximizing the entropy of the distribution subject to a relaxed constraint that feature expectations be only close to feature averages over sample locations rather than exactly equal to them. MaxEnt allows modeling only with presences.

The system was modeled also adding absences with the following criteria: (i) absences are not too close to Snowy Plover occurrences; (ii) absences are not too close to each other; (iii) absences are not in obviously unsuitable areas (e.g., in the middle of the ocean, inland, or in urban areas) where Snowy Plovers do not nest.

23.3.3 Species Viability and Metapopulation Dynamics (RAMAS)

An important aspect of future changes in habitat is their effect on species viability. At the metapopulation level, the models will have dynamic spatial structure and thus will incorporate future predicted changes in the species' habitat, including habitat loss and degradation, landscape fragmentation, and climate-related shifts in species' ranges. These habitat changes can be predicted by the models discussed, thus linking climatic and species models. The variables used in predicting dynamic changes in habitat will include climatic variables, including predicted or hypothesized changes in sea level, frequency of severe hurricanes, and frequency and timing of heavy precipitation in the next several decades. In addition, predicted changes in human land use will be incorporated into the dynamics of habitats. This is especially important for shorebirds, which are sensitive to human disturbance during their nesting seasons [43].

Dynamic spatial structure refers to temporal changes in the location and number of populations in a metapopulation. These changes will be based on changes in the habitat maps, which will be a function of climate change projections, as described above. Determining the temporal dynamics of spatial structure requires calculating the lineage of habitat patches, as they merge, split, appear or disappear, based on the changes in the habitat map [19]. Although incorporating these changes into a metapopulation model may be complicated when there are multiple simultaneous changes, this problem has been solved [2] and the resulting methodology has been implemented in the software we will use [6, 7]. The method has previously been applied to landscape changes brought about by timber harvest, succession, and natural disturbances [5, 7, 79]. The modeling we will do for this project will use the same approach, the only difference being that landscape dynamics will be driven by sea level rise due to climate change. Potential application of these models to climate change has been proposed by Akçakaya et al. [4], and is currently being explored by a team of climate and demographic modelers [40].

23.3.4 Risk-Based Decision Analysis for Adaptive Management

The primary advantage of an integrated approach is to have the ability to assess different sets of ecosystem data and modeling results and to build ever-expanding models, a common pitfall of adaptive management implementation. Climate change and ecosystem issues are inherently challenging and require greater amounts of coordination, consensus, and complementarity among people, their management processes, and their systems analysis tools [30]. MCDA, coupled with risk assessment for integrating heterogeneous scientific information (e.g., monitoring data, modeling, risk assessment), as well as for explicitly incorporating the value judgments of technical personnel and stakeholders to decide on the best course of action. MCDA represents a collection of approaches for structuring the decision-making process to organize the information provided by site-specific sampling and climate change modeling and the information resulting from decision maker intuition, environmental factors and situation criticality [41]. Utility theory is used to integrate this information into a score for each of the alternative action plans being evaluated within the analysis. MCDA offers the structure and quantitative approaches that can be used together as an exploratory tool for considering the full range of issues germane to a problem/solution in a systematic, rational, and efficient manner.

23.3.5 Global Sensitivity and Uncertainty Analysis of TER-S Models

23.3.5.1 The Role of Uncertainty in an Integrated Risk Management Framework

Integrated climate and ecological models are often complex and require a large number of inputs. Such mathematical models are built in the presence of uncertainties of various types (input variability, model calibration data, and scale). In addition, there is a growing interest in evaluating the contribution of model structural uncertainty (i.e., from model algorithms and design) to the overall uncertainty of the model outputs [10, 11, 25]. If model uncertainty is not evaluated formally, the science and value of the model will be undermined. The issue of uncertainty of model outputs has implications for policy, regulation, and management, but the source and magnitude of uncertainty and its effect on ecological assessment has not been studied comprehensively [55]. Reckhow [67] proposed that although uncertainty assessment can improve risk assessment and decision making, it does not eliminate uncertainty nor change the fact that, because of uncertainty, some decisions will have consequences other than those anticipated. Rather, the explicit integration of uncertainty in modeling studies should improve environmental management and decision making.

Incorporation of these uncertainty issues within adaptive, ecosystem management challenges such as climate change and TER-S demands an organized and methodical tool set that can help to parse through the often disparate and complex data that are integrated within an adaptive management framework. Recently developed tools that can be successfully integrated into a scientifically defensible and decision-useful suite of methods and tools include habitat-based metapopulation models with dynamic spatial structure [6, 8, 7] for estimating species viability under future habitat changes, global sensitivity/uncertainty analysis methods [39, 55, 69], and integration/decision analysis tools [41, 42, 48].

An important aspect of the framework is a comprehensive analysis of uncertainties, which result from measurement errors, inadequate understanding of natural and human processes and their interactions, and, especially in the case of climate change, from unpredictability of the society's response to the threat of global warming. Accordingly, a comprehensive sensitivity analysis is utilized by running a large number of simulations, each simulation with a unique combination of the uncertain input parameters and/or functions. The role of *uncertainty analysis* is to propagate all these uncertainties into a model output, while *sensitivity analysis* is used to determine the strength of the relation between a given uncertain input and a model output. Thus sensitivity analysis identifies the key contributors to uncertainties, while uncertainty analysis quantifies the overall uncertainty, so that together they contribute to a reliability assessment of the model [70].

Input factors of interest in the sensitivity analysis are those that are uncertain; that is, their value lies within a finite interval of non-zero width. The sensitivity and related uncertainty of a model output to a given input factor has been traditionally expressed mathematically in terms of the derivative of the model output with respect to the input variation, sometimes normalized by either the central values where the derivative is calculated or by the standard deviations of the input and output values [35]. These sensitivity measurements are "local" because they are fixed to a point (base value) or narrow range where the derivative is taken. These local sensitivity indexes are classified as "one-parameter-at-a-time" (OAT) methods; i.e., they quantify the effect of a single parameter by assuming all others are fixed [68]. Local OAT sensitivity indices are only efficient if all factors in a model produce linear output responses, or if some type of average can be used over the parametric space. Often, the model outputs' responses to changes in the input factors are non-linear, and an alternative "global" sensitivity approach, where the entire parametric space of the model is explored simultaneously for all input factors, is needed. The advantage of the global approach over a local OAT method is that it results in the ranking of parameter importance and provides information not only about the direct (first-order) effect of the individual factors over the output, but also about their interaction of higher-order effects. This approach allows one to also identify the effect of model structure (i.e., alternative model complexity levels) on the uncertainty and sensitivity of the input factors [55].

Often when model sensitivity analysis is performed, simple derivation techniques (variation of the model output over the variation of the model input) are employed. As an alternative, sometimes a crude variational approach is selected in which, instead of a derivative, incremental ratios are taken by moving factors one at a time from the base line by a fixed amount (for example, 5%) without prior knowledge of the factor uncertainty range. Traditional sensitivity analysis methods are limited since they only explore a prescribed (and usually small) parametric range, and can only consider efficiently a few inputs since they are based on OAT approaches [68].

When the model output response is non-linear and non-additive, as with most complex ecological model outputs, the derivative techniques are not appropriate and global techniques that evaluate the input factors of the model concurrently over the whole parametric space (described by probability distribution functions) (PDFs) must be used. Different types of global sensitivity methods can be selected based on the objective of the analysis [69]. This study proposes a model evaluation framework [55] around two such modern global techniques, a screening method [54] and a quantitative variance-based method [23, 73]. The screening method allows an initial reduction in the number of parameters to use in the quantitative Sobol [73] sensitivity and uncertainty analyses. The proper use of global sensitivity methods can yield four main products for this application [69]:

1. Assurance on the model's behavior (absence of errors)
2. Ranking of importance of the parameters for different outputs
3. Effect of changing modeling structure
4. Type of influence of the important parameters (first order or interactions)

In addition, based on the outputs derived from this analysis, a complete uncertainty assessment of the model application can be obtained and used as the basis for the risk-informed decision analysis of proposed management scenarios for the region.

Global uncertainty and sensitivity analyses rely on pseudorandom number sample generation (PNG) of the model input factors from probability distributions. The emphasis of the analysis is to sample a set of points from joint probability distributions of the selected model input factors; that is, the sample distribution. PNG-based uncertainty and sensitivity analyses involve performing multiple model evaluations with stochastically selected values for model inputs, and using the results of these evaluations to determine (1) the degree of uncertainty in model predictions and (2) the input variables responsible for the uncertainty. In general, the proposed analysis procedure follows six main steps:

- *Step 1*: PDFs are constructed for uncertain input factors.
- *Step 2*: input sets are generated by sampling the multivariate input distribution, according to the selected global method (i.e., Morris method for the initial screening and extended FAST for the quantitative refining phase).
- *Step 3*: RAMAS/GIS/Metapopulation model simulations are executed for each input set.
- *Step 4*: global sensitivity analysis is performed according to the selected method.
- *Step* 5: if the Morris screening method is selected, it results in a subset of important parameters and steps 2–4 are repeated only for those important parameters using the extended FAST method.
- *Step* 6: uncertainty is assessed based on the outputs from the extended FAST simulations by constructing PDFs/cumulative distribution functions (CDFs) and statistics of calculated errors.

23.3.5.2 Screening Method: Morris

The screening method proposed by Morris [54] and later modified by Campolongo and others [13] is proposed in this study because it is relatively easy to apply, requires very few simulations, and its results are easily interpreted [68]. Morris [54] proposed conducting individually randomized experiments that evaluate the elementary effects (relative output differences) of changing one parameter at a time. Each input may assume a discrete number of values, called levels, which are selected within an allocated range of variation for the parameter. For each parameter, two sensitivity measures are proposed: (1) the mean of the elementary effects (μ), which estimates the overall effect of the parameter on a given output; and (2) the standard deviation of the effects (σ), which estimates the higher-order characteristics of the parameter, such as curvatures and interactions. Because the model output can be non-monotonic, Campolongo and others [13] suggested considering the distribution of absolute values of the elementary effects (μ^*) to avoid the canceling of effects of opposing signs. The number of simulations required (N) to perform the Morris analysis is expressed as:

$$N = r\left(k+1\right) \tag{2}$$

where r is the sampling size for search trajectory ($r=10$ produces satisfactory results), and k is the number of factors. Although elementary effects are local measures, the method is considered global because the final measure, μ^*, is obtained by averaging the elementary effects, and this eliminates the need to consider the specific points at which they are computed [68]. Morris [54] recommended applying μ (or μ^* thereof) to rank parameters in order of importance, and Saltelli and others [71] suggested applying the original Morris measure, σ, when examining the effects induced by interactions. To interpret the results in a manner that simultaneously provides insight about the parameter ranking and potential presence of interactions, Morris [54] suggested plotting the points on a $\mu(\mu^*)$-σ Cartesian plane. Because the Morris method is qualitative in nature, it should only be used to assess the relative parameter ranking.

23.3.5.3 Analysis of Variance Screening Method: Extended Fourier Amplitude Sensitivity Test (FAST)

A variance-based method such as FAST can be used to obtain a quantitative measure of sensitivity [23]. This technique decomposes the total variance ($V=\sigma^2{}_Y$) of the model output $Y=f(X_1, X_2, \ldots, X_k)$ in terms of the individual factors X_i, using spectral analysis so that:

$$V = \sigma^2{}_Y = V_1 + V_2 + V_3 + \ldots + V_k + R \quad (3)$$

where V_i is the part of the variance that can be attributed to the input factor X_i alone, k is the number of uncertain factors, and R is a residual corresponding to higher-order terms. The first-order sensitivity index, S_i, which is defined as a fraction of the total output variance attributed to a single factor, can then be taken as a measure of global sensitivity of Y with respect to X_i; that is:

$$S_i = V_i / V \quad (4)$$

To calculate S_i, the FAST technique randomly samples the k-dimensional space of the input parameters using the replicated Latin hypercube sampling (r-LHS) design [53]. The number of evaluations required in the analysis can be expressed as:

$$N = M(k+2) \quad (5)$$

where M is a number between 500 and 1,000. For a perfectly additive model, $\Sigma S_i = 1$; that is, no interactions are present and total output variance is explained as a summation of the individual variances introduced by varying each parameter alone. In general, models are not perfectly additive, and $\Sigma S_i < 1$.

The FAST analysis was extended to incorporate the calculation of the total order effects through the total sensitivity index, S_{Ti}, calculated as the sum of the first and all higher-order indices for a given parameter X_i. For example, for X_1:

$$S_{T1} = S_1 + S_{1i} + S_{1jk}, + \ldots + S_{1\ldots n} \text{ and } \mathrm{S}_{T1} - \mathrm{S}_1 = \mathrm{S}_{1i} + \mathrm{S}_{1jk}, + \ldots + \mathrm{S}_{1\ldots n} \quad (6)$$

For a given parameter X_i, interactions can be isolated by calculating $S_{Ti} - S_i$, which makes the extended FAST technique a powerful method for quantifying the individual effect of each parameter alone (S_i) or through interaction with others ($S_{Ti} - S_i$). An additional benefit of the extended FAST analysis is that because the results are derived from a randomized sampling procedure, they can be used as the basis for the uncertainty evaluation by constructing CDFs for each of the selected outputs. This could lead to an efficient Monte Carlo type of uncertainty analysis, if only the sensitive parameters identified by the Morris screening method are considered the source of uncertainty [55].

23.4 Results: Exploring the Framework from Land Cover Projections, Habitat Suitability, Metapopulation Dynamics, Global Sensitivity/Uncertainty Analysis, and MCDA

This section provides summarized methodological information as to how each analysis technique is conducted along with early proof-of-concept results for some of the methods.

23.4.1 Land Cover Change

The Florida Gulf coast was simulated using SLAMM. The focus was on the Eglin AFB depicted in Fig. 23.3. The Florida Gulf coast simulations are shown in Fig. 23.4. The field-scale ambient variability of many inputs has been reported to be modeled adequately using normal or log-normal distributions [35]. Because of the lack of data needed to estimate mean and standard deviations for PDFs assumed to be Gaussian, the β-distribution was used to assign proper values so that shape factors fit an approximate log-normal distribution. The β-distribution is generally used as a rough model in the absence of sufficient data. When only the range and a base (effective) value are known, a simple triangular distribution can be used. If an input factor range is known but there is no additional information about the probability of the different values within their range, a uniform distribution (U-distribution) can be used. To characterize sensitivity and uncertainty, each SLAMM input factor was assigned a PDF based on the range of values obtained from a comprehensive literature review and our team expert's knowledge. The range for each parameter was selected to cover all physically realistic values.

Several types of model outputs were selected in the analysis for Snowy Plover populations and other important storages in the system. For mobile quantities, averages across the external domain boundary were calculated at the end of the simulation, or as an average over the entire simulation. For stabile output quantities—i.e., those that don't move out of the domain—variation at the end of the simulation was estimated as the difference across the entire domain between the mean value at the beginning and end of the simulation.

These preliminary results from SLAMM presented in this paper are a summary of a more detailed technical model/uncertainty analysis [15]. The results presented here show how information from Global Sensitivity/Uncertainty Analysis provides a strong baseline for additional decision analysis efforts. The SLAMM/GSUA

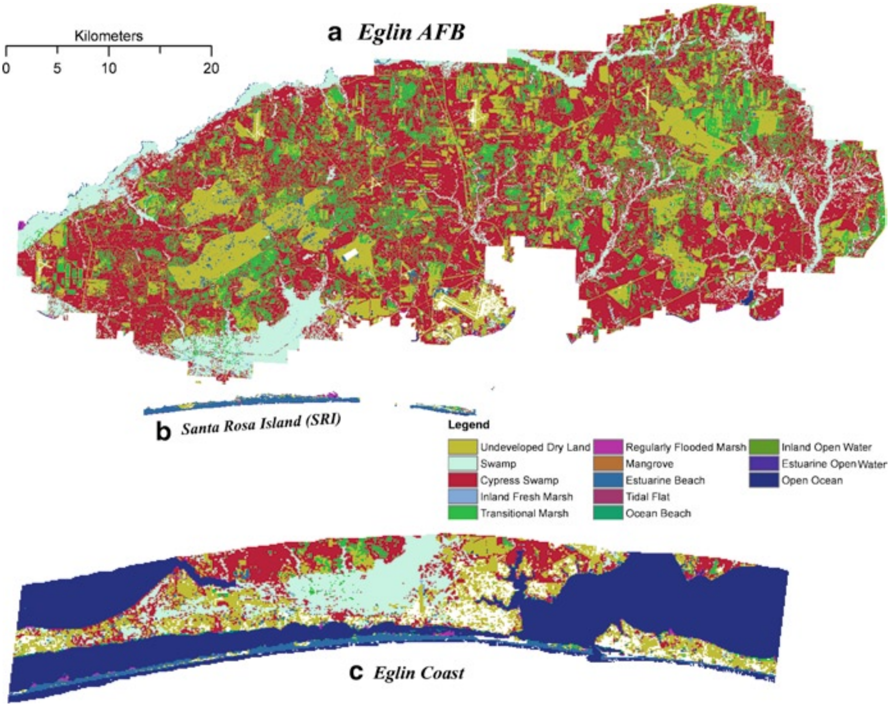

Fig. 23.3 Eglin AFB. Land cover of the Eglin AFB [70]. Upper plot: the whole military installation of Eglin AFB including Santa Rosa Island at 30 m × 30 m resolution. Bottom plot: Santa Rosa Island at 30 m × 30 m resolution used for training purposes and breeding ground if the Snowy Plover [14]

results showed that the variability in the change in area of the higher-elevation wetlands (swamps and inland fresh marsh) was attributed in general to the DEM vertical error for the lower-elevation range zone (0–1 m) (95–99%) and historic trend of sea level rise (1–2%). A comparison among DoD installations land cover changes is represented in Figs. 23.5 and 23.6 shows a comparison of the loss of the beach habitat in time between Eglin AFB and Santa Rosa Island (managed by Eglin AFB).

Interactions between input factors for these wetlands were negligible. Higher-elevation wetlands showed a general decrease in area from 2060 to 2100 and from minimum to maximum sea level rise scenarios. For lower-elevation wetlands (salt marsh, tidal flat, and beach), the variance in the output was mostly driven by varying percentages of the DEM vertical error for the lower-elevation range zone (0–1 m), historic trend in sea level rise, salt marsh vertical accretion, and beach/tidal flat sedimentation rate, with the latter two factors outweighing the others. As the elevation of the wetland decreased (due to sea level rise), the number of factors affecting the variance of the output increased adding complexity to the model outputs. Interactions

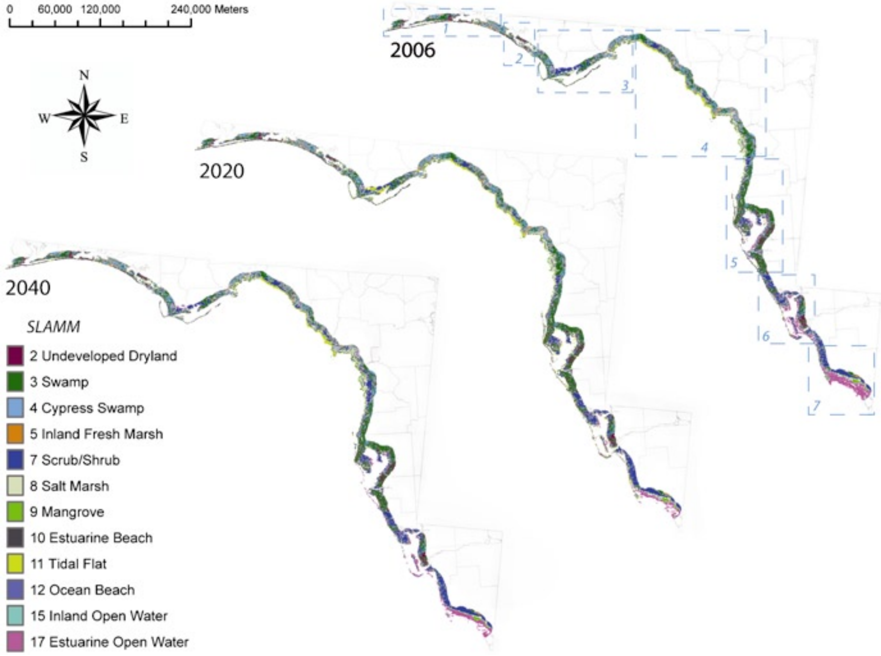

Fig. 23.4 Simulated land cover patterns. Predicted land cover in time represented as SLAMM classes for the years 2006, 2020, and 2040. The domain has been divided into seven areas because different sea level rise trend and tidal dynamics: Pensacola-Eglin (**1**), Tyndall (**2**), East Apalachee Bay (**3**), Big-Bend (**4**), Tampa Bay (**5**), Ft. Meyers (**6**), and North Everglades (**7**). For each area the SLAMM parameters are different [26]

were observed for historic trend of sea level rise, salt marsh vertical accretion, and beach/tidal flat sedimentation rate, which suggested that a unique combination of these factors with other input factors can result in extreme values of the output. This is specifically manifested in the variance of salt marsh which showed a bimodal distribution with one peak suggesting an increase in the area while the other suggesting a decrease. This implies that there exist unique combinations of input factors that can result in salt marsh being lost or gained. The predicted fate of the barrier island in Eglin AFB therefore depends on these unique combinations of input factors. Overall, SLAMM's output was found to be most sensitive to the DEM vertical error for the lower-elevation range zone (0–1 m), historic trend in sea level rise, salt marsh vertical accretion, and beach/tidal flat sedimentation rate [25]. This result was consistent with the model's theoretical framework since these factors were the main variables which determined the minimum elevation of the cell and thus, its fate. This further confirmed that the most important processes involved in the fate of the coastal habitat in Eglin AFB were inundation (reduction in elevation due to sea level rise) and accretion/sedimentation (Fig. 23.7).

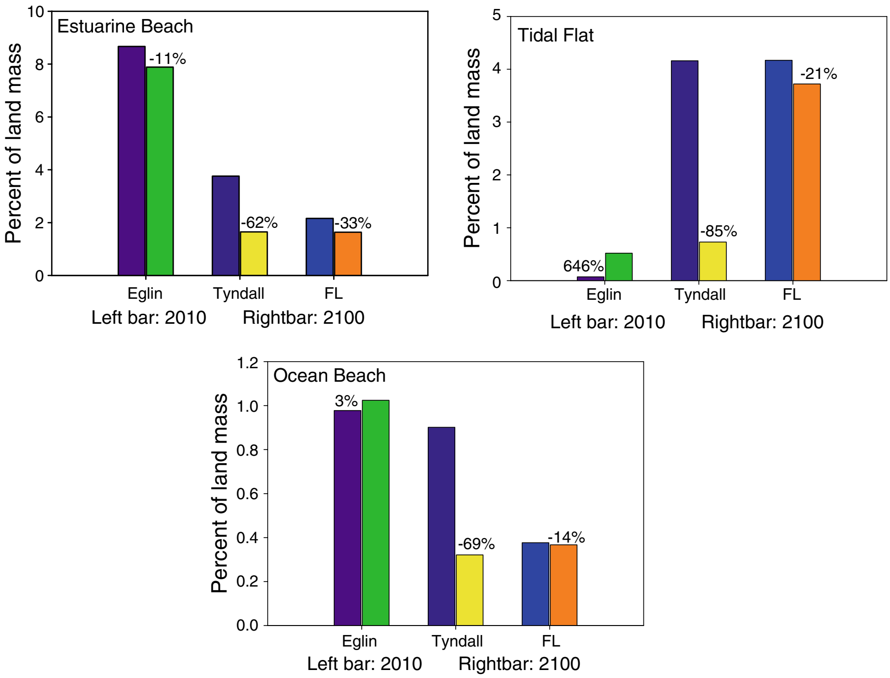

Fig. 23.5 Snowy Plover suitable habitat-class changes from 2010 to 2100. Comparison of the changes in the beach habitat, tidal flat and ocean beach for Eglin, Tyndall, and the entire Gulf Coast of Florida between 2010 (*purple, blue, and light blue bars*) and 2100 (*green, yellow, and orange bars*) for Sea level Rise (SLR) = 2.0 m. Numbers on top of the bars represent the percent change in area between these two time periods [20]

23.4.2 Suitability Index in Time

Here we describe the methods we used for deriving the habitat suitability maps. The habitat suitability model chosen for the integrated modeling is MaxEnt. The dependent variable is occurrence of a Snowy Plover nest. Thus, it is binary, and it is recorded during the breeding season. The populations on the North Coast and along the Gulf Coast of Florida are treated as independent and both the models are able to fit them. The resulting function to predict the habitat suitability in the Gulf population was used to validate the model with the North population and vice versa. Test of the goodness of fit with the area under the receiver operating characteristic (ROC) curve (AUC) is adopted to see how well the function predicts the known nest locations. The area of the Tyndall and Eglin AFBs are selected also as testing areas for running the models, because they constitute focus-areas of the project and to evaluate the effect of the scale on the habitat suitability maps. The models are run inside a coastal zone that is no more extended than 1,000 m from the occurrences data. The resolution

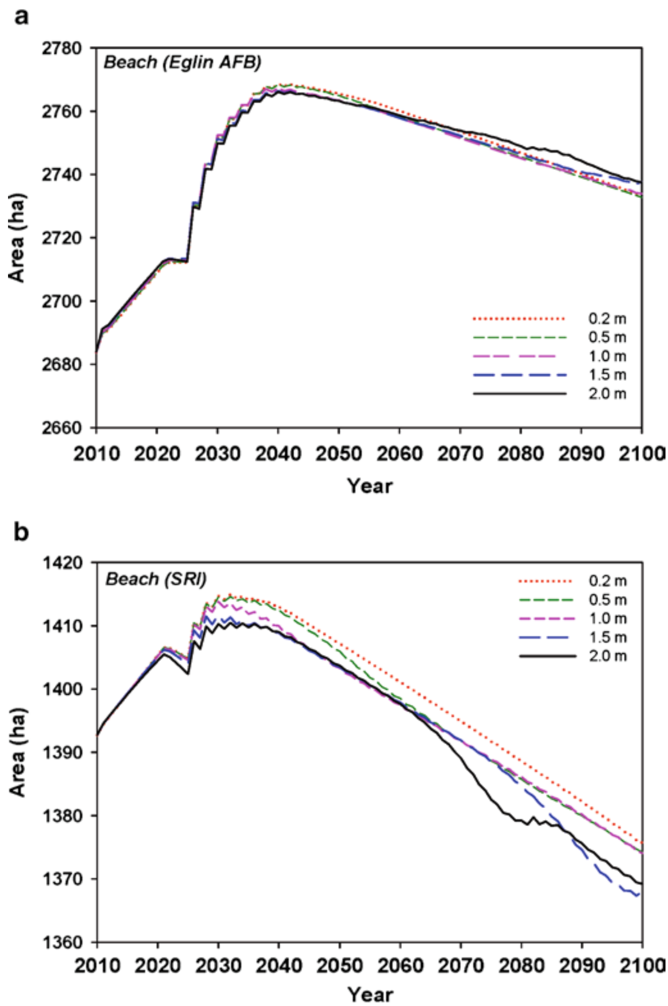

Fig. 23.6 Beach habitat changes at Eglin AFB for different SLR scenarios ([0.2; 2.0] m). Changes in the area of the beach habitat consists of estuarine beach, tidal flat, and ocean beach for (a) Eglin AFB and (b) Santa Rosa Island at different SLR [20]

of the land cover has been chosen to be a maximum of 120 m since this is the estimate of the home range size of Snowy Plovers for the Pacific Coast Population.

The scale to which the model is run; that is, the spatial extent of the geographical area considered, the resolution of the environmental layers, and the shape of the domain modeled that is determined by the extent of the buffer zone around the presences points, have an effect on the computed habitat suitability [17]. This has several effects on the species conservation planning under climate change predictions (global climate models which are frequently used in the creation of SDMs usually consist of

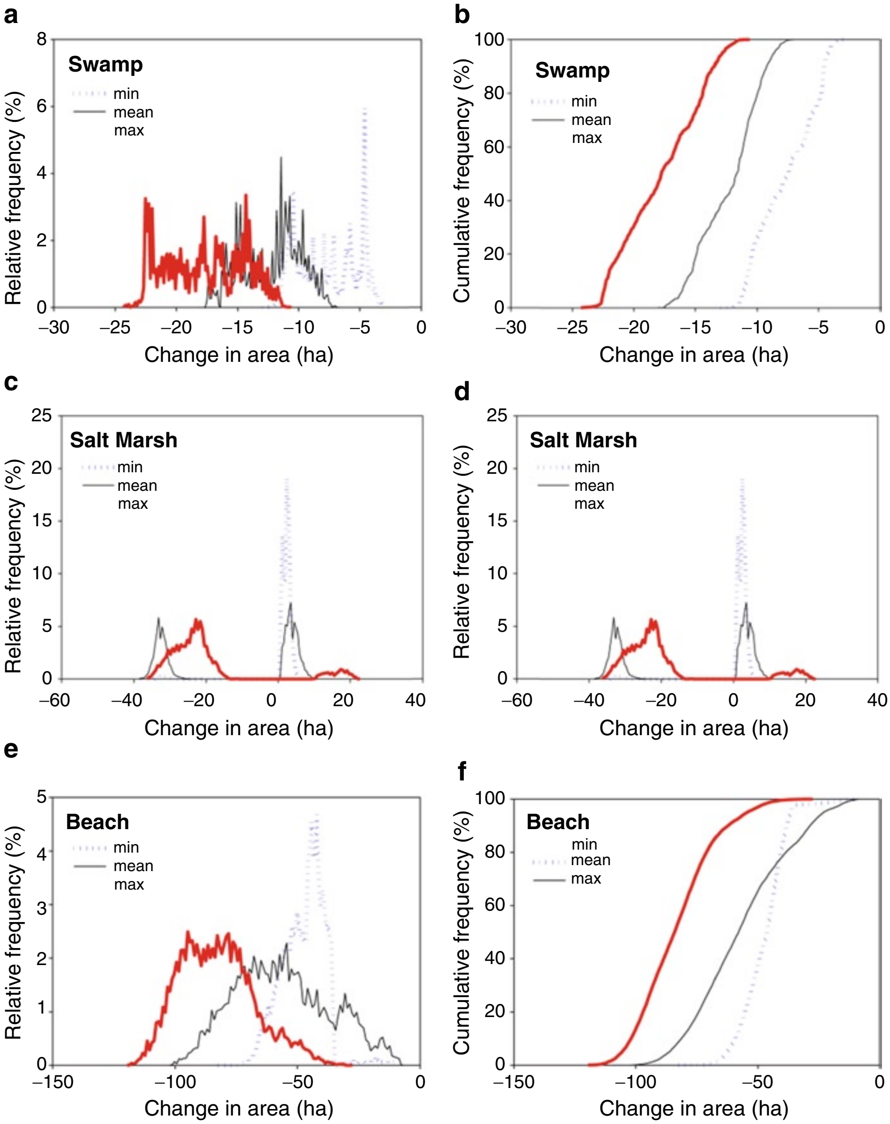

Fig. 23.7 Global uncertainty analysis for SLAMM classes of Santa Rosa Island. Global uncertainty analysis for (**a**–**b**) swamp, (**c**–**d**) salt marsh, and (**e**–**f**) beach considering the minimum, mean, and maximum SLR scenario for 2100 for the portion of Santa Rosa Island managed by Eglin AFB. The sea level rise here is assumed to be 1 m [22]

50–100 km size grids), which could lead to over-prediction of future ranges in species distribution modeling. This can result in the misidentification of protected areas intended for a species future habitat. Issues like the incorrect GPS locations of presences that leads to a mis-assignment to the land cover classes also affected the

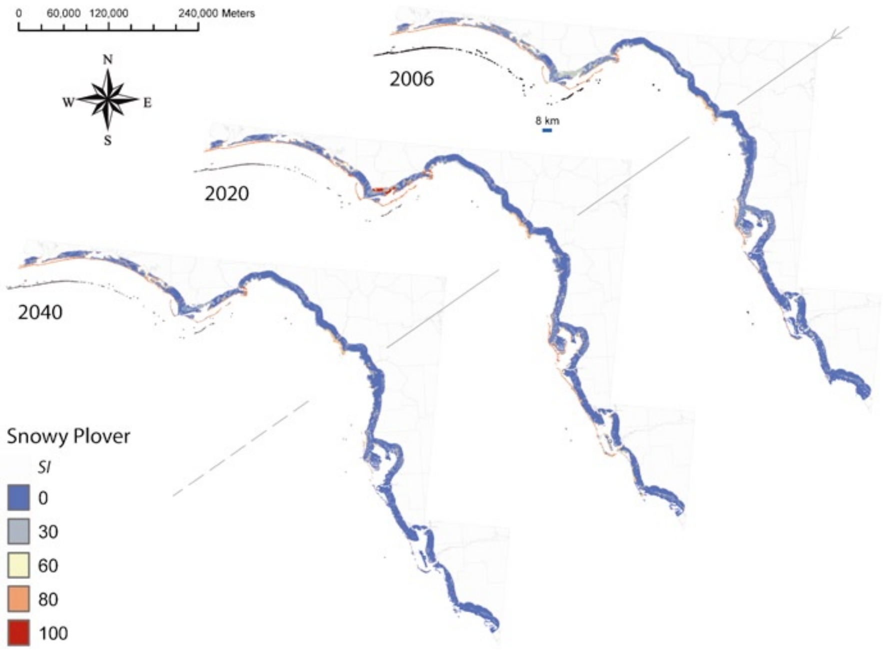

Fig. 23.8 Simulated Snowy Plover suitability index patterns. Suitability Index in time for the Snowy Plover derived from the habitat suitability models (MaxEnt) for the years 2006, 2020, and 2040. The suitable patches determined by the patch-delineation algorithm are represented below each habitat suitability pattern [26]

final results [18]. The habitat suitability maps are the inputs of the metapopulation model. Figure 23.8 shows the suitability index patterns in time. The suitability index is computed by ranking in ranges the estimated probability of occurrence [19].

23.4.3 Snowy Plover Metapopulation Dynamics

We constructed a series of habitat-based metapopulation models of the Florida Snowy Plover, using and integrating available data on habitat, demography, and behavior into models that will be used to calculate future population viability and expressed in such metrics as expected total population size, expected minimum population size, probability of persistence, and probability of recovery. The models are implemented in RAMAS software, and widely used for ecological risk analysis (e.g., see Akçakaya et al. [3] and www.ramas.com/ramasapp.htm). Model design and application follows the conceptual model in Fig. 23.4. Each simulation (or run) of the model simulates the species future population trajectory for a period of 20–50 years, and includes a minimum of 1,000 replications (iterations). Multiple replications are used to incorporate estimated natural variability (e.g., probabilistic occurrence of hurricanes, and year-to-year variation in rainfall and other environmental factors). Thus, the predictions of the model from a single simulation run are probabilistic, predicting the viability of the species on terms of the risk of decline or extirpation of the species, or its chances of recovery. To determine the contribution of DoD lands to the viability of these populations, we run each model with and without the site we are focusing on. The difference in Snowy Plover population viability between these two models (with and without the focal site) provides a measure of the contribution of the site to the overall viability. TER-S models include habitat maps created using three types of information: (1) data on breeding Snowy Plover distribution and wintering Snowy Plover distribution, (2) maps of variables related to habitat requirements of the species, and (3) habitat requirements collated from the literature. At the population level, the models will incorporate stochasticity (natural temporal variability) and population structure (age or stage structure). The data for these will be obtained from Lott [49–51], as well as unpublished modeling work on the Snowy Plover [8]. The models also have dynamic spatial structure, temporal changes in the location and number of populations, and thus will incorporate future predicted changes in the species' habitat, including habitat loss and degradation, landscape fragmentation, and climate-related shifts in species' ranges. The final results of the RAMAS model are shown in Figs. 23.9 and 23.11.

23.4.4 Involving Biocomplexity: Computational and Theoretical Achievements

Relationships among biological, ecological, geomorphological, and climatologic variables have been investigated throughout the study. Convertino et al. [19–21] investigated the relationship among nesting and wintering probability of shorebirds and tropical cyclones, renourishment interventions, and the correlation among the fractal dimensions of the patches and of the coastline.

The odds ratio is the ratio of the odds of a nesting ground in the spring following a year with at least one tropical cyclone to the odds of a nesting ground in the spring following a year without a tropical cyclone. The frequencies are based on 10^4 Monte Carlo samples. The median odds ratio is 7 and the mean is 11. The maximum likelihood estimate is a lognormal distribution (red curve) and the coefficient of determination is $R^2=0.87$. Figure 23.10b is the posterior probabilities of absence $P(A>a)$ of the odds ratio for Snowy Plover in the breeding season, and Snowy Plover, Piping Plover, and Red Knot in the wintering season. The odds ratio is the ratio of the odds of a nesting or wintering ground in the spring following a year with at least one renourishment event to the odds of a nesting or wintering ground in the spring following a year without a renourishment intervention. For the breeding Snowy Plover the median odds ratio is 2.5 and the mean is 4.9. For the wintering Snowy Plover, Piping Plover, and the Red Knot the median odds ratio is 2.3, 3.1, and 0.8 respectively. The maximum likelihood estimate is a lognormal distribution with different values of the shape parameter (histogram only for Snowy Plover) and the

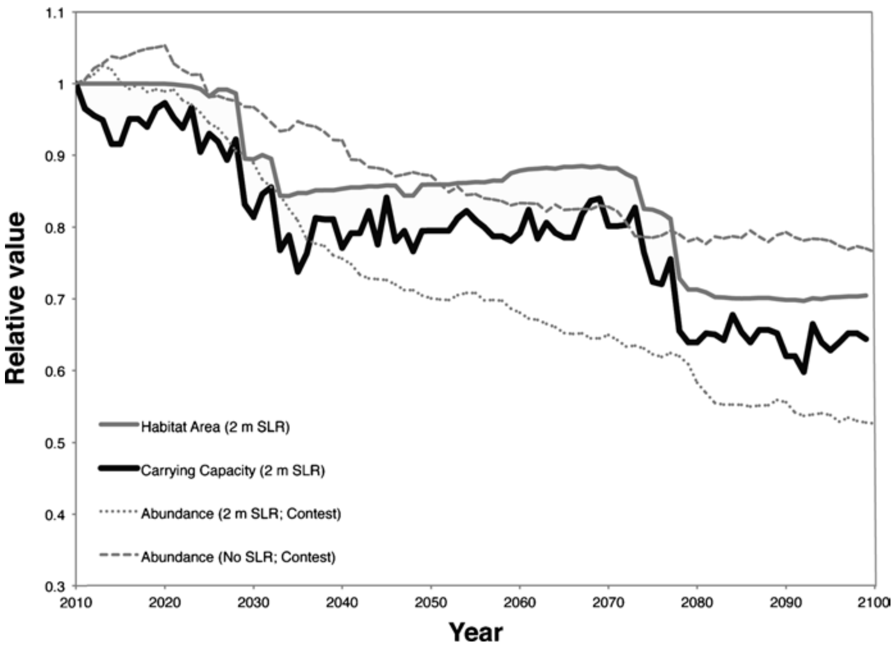

Fig. 23.9 The projected declines in: the total area of Snowy Plover habitat predicted by the habitat model, based on the projections of the 2 m sea level rise model (Habitat Area); the total carrying capacity of populations identified by RAMAS, based on the habitat model (Carrying Capacity); and total metapopulation abundance (Population size), averaged over 1,000 replications, with 2 m sea level rise (2 m SLR) and without SLR (No SLR) considering the contest density dependence function. Simulations considering 1 m SLR gave smaller declines but qualitatively similar results [1]

coefficient of determination for Snowy Plover, Piping Plover, and Red Knot is on average $R^2 = 0.92$.

Figure 23.11, as in Convertino et al. [19], shows the correspondence between the fractal dimension of the suitable patches and the fractal dimension of the species-dependent habitat coastline.

23.4.5 Risk-Based Decision Analysis and MCDA

This framework provides a systematic method to assess and plan for the level of information and model representation necessary to match current system understanding with management objectives. We utilized MCDA coupled with risk assessment for integrating heterogeneous scientific information (e.g., monitoring data, modeling, risk assessment), as well as for explicitly incorporating the value judgments of technical personnel and stakeholders to decide on the best course of action (adaptive management). Environmental data are used to develop a weighting structure for the

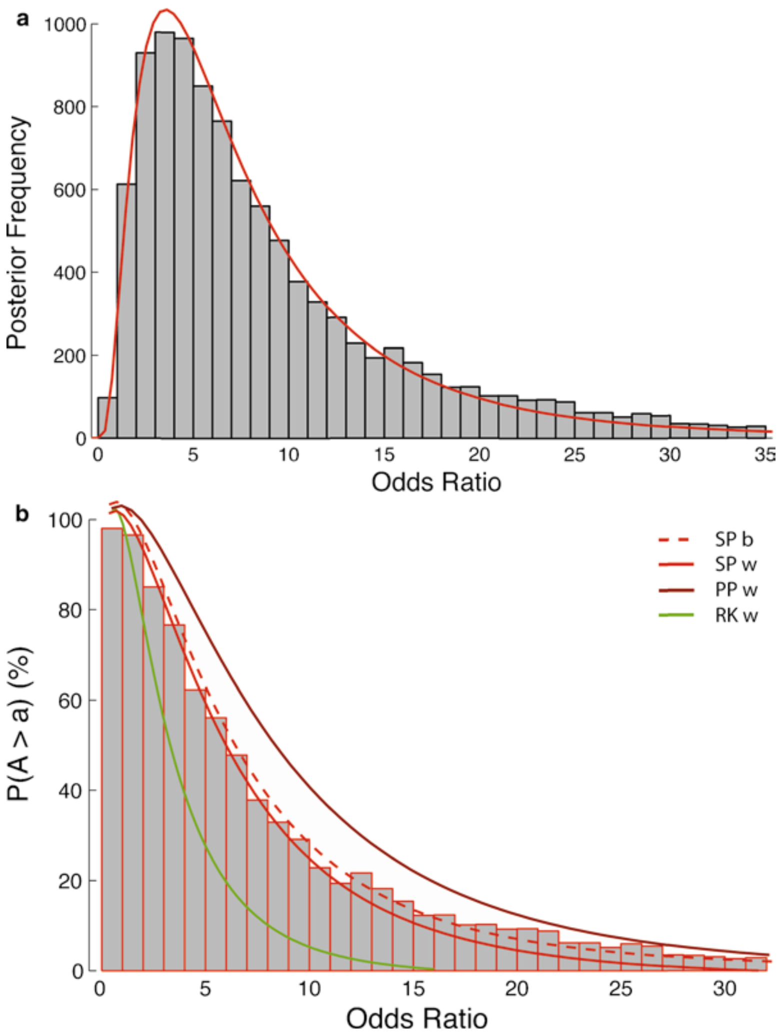

Fig. 23.10 Bayesian inference model for Snowy Plover vs. tropical cyclones and beach renourishment. (**a**) Posterior frequencies of the odds ratio considering the odds of a nesting ground in the spring following a year with at least one tropical cyclone to the odds of a nesting ground in the spring following a year without a tropical cyclone. (**b**) Posterior probabilities of absence P(A > a) of the odds ratio for Snowy Plover in the breeding season, and Snowy Plover, Piping Plover, and Red Knot in the wintering season. The odds ratio is the ratio of the odds of a nesting or wintering ground in the spring following a year with at least one renourishment event to the odds of a nesting or wintering ground in the spring following a year without a renourishment intervention [21]

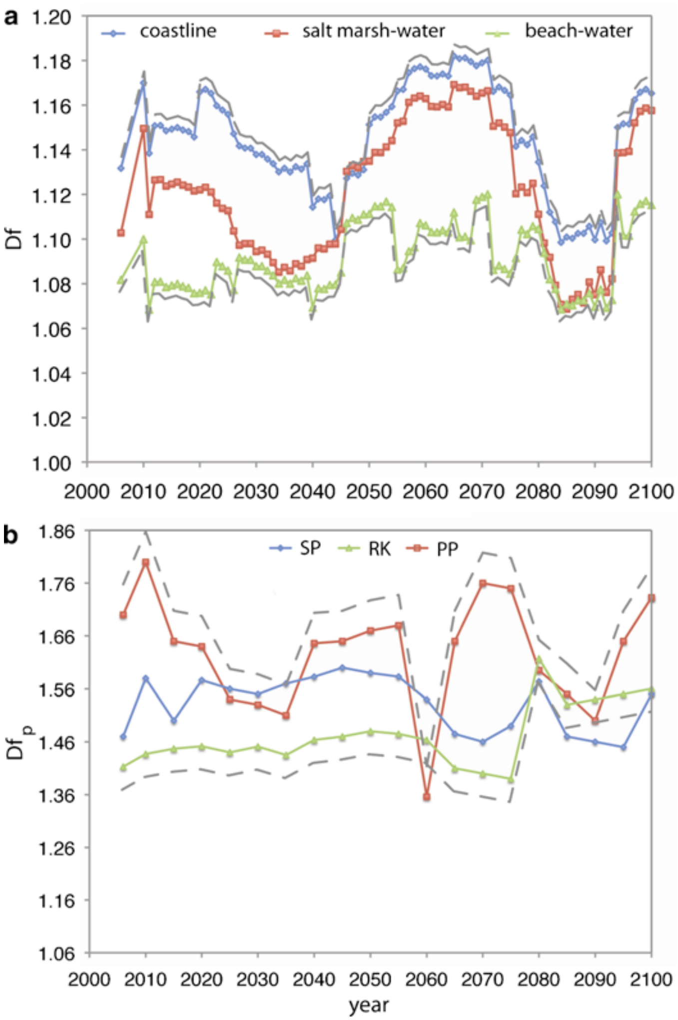

Fig. 23.11 Fractal dimension time-series of the shorebirds patches and of the Florida Gulf coastline. (**a**) Time series of the fractal dimension D_f of the coastline (*blue line*) and of the salt-marsh (*red*) and beach (*green*) habitat coastlines, determined by the box-counting algorithm. (**b**) Fractal dimension D_{fp} in time of the patches for Snowy Plover (*blue dots*), Piping Plover (red), and Red Knot (*green*) derived from the Korcak's law. The gray line represents the 95% confidence interval [26]

set of metrics that reflects military priorities and interests. Utility theory is used to integrate this information into a score for each of the alternative action plans being evaluated within the analysis. We used the habitat suitability maps to create seasonal training maps as a function of the training windows of the interested DoD installations. The proof-of-concept MCDA/adaptive management structure is based on the methodology and criteria described in Gregory et al. [30] to both assess the viability of

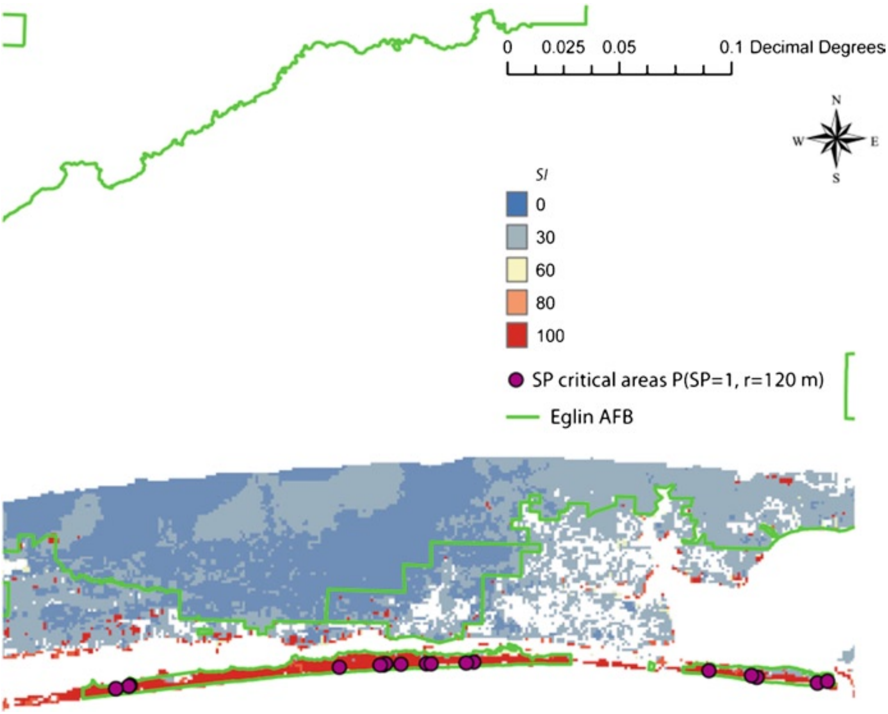

Fig. 23.12 Predicted habitat suitability index map (SI) for Snowy Plover in 2,100 in the coastal area of Eglin AFB (Santa Rosa Island). The model has been run for the whole Gulf coast. The higher the SI, the higher the probability to find a Snowy Plover breeding ground. The Snowy Plover critical areas (max predicted SI and recorded presence) where training should be avoided are depicted in violet. The respected area should be minimum 120 m (the home-range of the Snowy Plover)

adaptive management and provide a useful and scalable structure to link site-based coastal management alternatives with greater coastal dynamics. A simplified MCDA structure is provided when coastal restoration alternatives are formulated and ranked. Gregory et al. [30] point out that adaptive management at large, multiscale, multi-agency sites pose significant pitfalls. They also point out that adaptive management efforts in smaller controlled areas may be useful and even coordinated with greater efforts.

Figure 23.12 shows an example of adaptive management. The habitat suitability map is used together with the recorded nesting locations to create spatial training windows for DoD troops. The Snowy Plover critical areas are taken proportional to the home range and they are located where the habitat suitability model assumes values greater than 0.6 and close to the recorded occurrences. The adaptive management is planned to be also seasonal to respect the different needs of DoD installations and shorebirds during the year. A multispecies adaptive management area is also planned to be built in the future (Fig. 23.13).

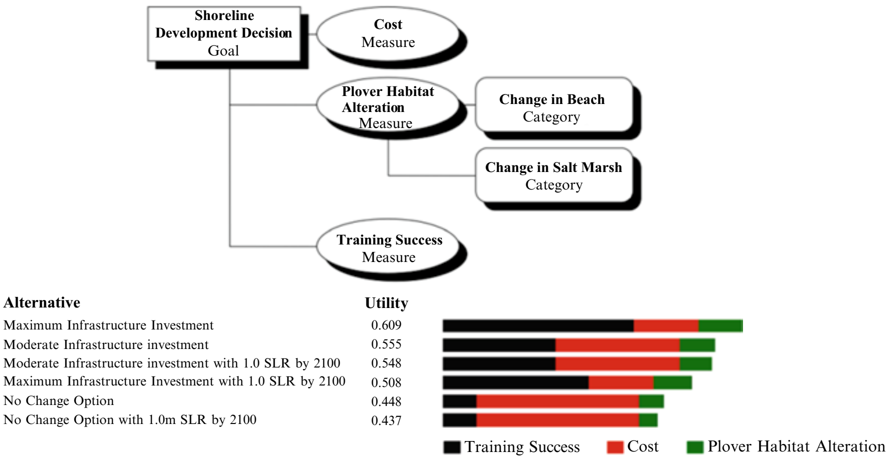

Fig. 23.13 Example of MCDA in which a utility value is calculated for each alternative. All the relevant criteria (training success, cost of ecological intervention, and plover habitat alteration) are used in the formulation of the utility value

23.5 Conclusions and Perspectives

This section provides a summary of the challenges highlighted by the results of the research.

- We created a robust modeling framework that can be applied to every species and coastal sites, and in particular to coastal DoD installations potentially affected by sea level rise risk due to climate change or inundation risk.
- The risk of habitat loss and species extinction of shoreline-dependent birds has been assessed in Florida. The Snowy Plover is a species at risk due to sea level rise and habitat use.
- Natural resource managers operate within the boundaries of their competence. Our results add quantifiable, ecologically sustainable training windows for DoD installations.
- The quantification of the complex interrelationship among biological, ecological, geomorphological, and climatologic variables is useful to discard a priori assumptions (e.g., negative influence of tropical cyclones) and to direct better conservation interventions like renourishments.
- The global sensitivity and uncertainty analysis has formulated scenarios for bimodal adaptive management due to the bimodality of the obtained results (e.g., loss or gain of salt marshes).

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Chapter 24
Recent Climate Change, Projected Impacts, and Adaptation Capacity in Iceland

H. Björnsson, T. Jóhannesson, and Á. Snorrason

Abstract The subpolar maritime climate of Iceland is characterized by relatively large interdecadal variations. Temperature measurements show that the nineteenth century was colder and more variable than the twentieth century. Iceland experienced rapid warming in the 1920s and relatively mild conditions prevailed until the 1960s, when colder conditions set in. In recent decades Iceland has again experienced significant warming and early this century the temperatures exceeded those attained during the mid-twentieth century warm period. The recent warming has been accompanied by significant changes in both physical and biological systems. These include glacier retreat, runoff changes and isostatic rebound, increased plant productivity and changes in tree limits. In coastal waters, the range of fish species is changing, reflecting warmer conditions. Socioeconomic impacts that can be related to the warming are already discernable, in the agricultural, transportation, and fishing sectors.

Climate model projections for Iceland indicate that continued warming is likely although interdecadal variability may lead to punctuated warming episodes. An adaptation strategy has to take into account the various uncertainties associated with the magnitude of climate change and the severity of the impacts as well as the vulnerability and adaptive capacity of societal systems. A comprehensive framework for dealing with adaptation is needed. It is argued that a risk management perspective is appropriate.

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24.1 Introduction

In good weather, the picturesque Snæfellsjökull ice cap (Fig. 24.1) can be seen across the bay from Reykjavík. In the 1864 novel *Journey to the Center of the Earth*, by Jules Verne, the ice cap serves as the entrance to a passage that led to the center of the earth. It is the only ice cap that can be seen from Reykjavík, and it has persisted for many centuries, at least since Iceland was settled in the ninth century AD. Recent measurements show that this ice cap is shrinking rapidly in size. This is but one example of climate change impacts in Iceland discussed in this article. The article will review evidence of climate change and climate change impacts in Iceland and discuss future projections and the scope for adaptation.

24.2 Recent Climate Change in Iceland

The climate of Iceland exhibits considerable variability on annual and decadal timescales. However, long-term temperature records from the weather station at Stykkishólmur, about 60 km from the Snæfellsjökull ice cap, show that during the last two centuries the climate of Iceland has warmed by about 0.7°C per century (see Fig. 24.2). In recent decades the warming has been very rapid, with significant impacts on many natural systems in Iceland.

Recent measurements show that the Snæfellsjökull ice cap, which has an average thickness of less than 50 m, thinned by approximately 13 m in the last decade. At the current rate of thinning it will disappear within this century (Fig. 24.3a).

Snæfellsjökull ice cap is not an isolated case in this regard; most monitored glaciers in Iceland are retreating . The thinning of large glaciers, such as the Vatnajökull ice cap, one of Europe's largest ice masses, reduces the load on the Earth's crust, and the crust rebounds. Consequently large parts of Iceland are now experiencing uplift (Fig. 24.3b). The uplift does not, however, reach to the urban southwest part of Iceland, where subsidence is occurring (the subsidence is occurring for reasons unrelated to climate change).

Changes are also evident in glacial river runoff, with earlier onset of the melting season and enhanced late summer melting [4]. The rapid retreat of glaciers not only influences glacier runoff but leads to changes in fluvial erosion from currently

Fig. 24.1 The Snæfellsjökull ice cap [3]

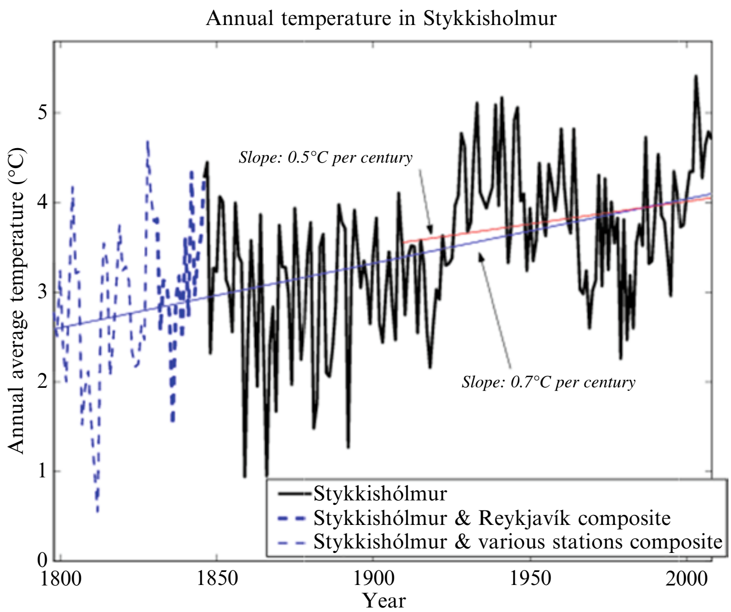

Fig. 24.2 Annual temperature at the weather station in Stykkishólmur from the early nineteenth century to the present day [4]

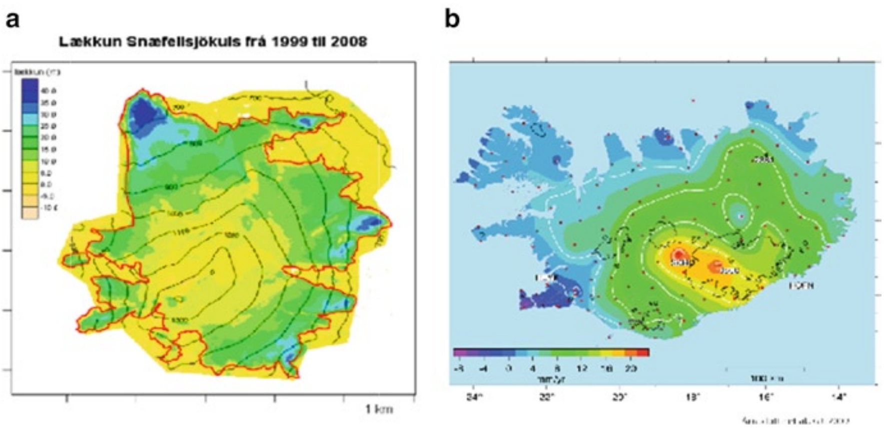

Fig. 24.3 (**a**) The changes in surface topography in of the Snæfellsjökull glacier from 1999 to 2008. The figure shows a widespread loss of ice, on average about 1.5 m per year, with largest drops in surface height towards the edge of the glacier. The only region where there as been an increase in surface height is at the top of the glacier. The thick line indicates the outline of the glacier in 2000 [5]. (**b**) vertical motion of the land surface in Iceland based on measurements from 1993 to 2004. Positive numbers indicate uplift; negative numbers indicate subsidence. Red dots show the station network [2].

Fig. 24.4 The bridge over Skeiðará, south Iceland. The bridge was built in the early 1970s over a large glacial river. In 2009, as a result of the retreat of the Skeiðarárjökull outlet glacier, the river changed course, leaving the bridge spanning mostly dry sand

glaciated areas and changes in the courses of glacier rivers, which may affect roads and other communication lines. A recent example of this is the change in drainage from Skeiðarárjökull, but due to thinning and retreat of the glacier, the outlet of the river Skeiðará moved west along the glacier margin and the river merged into another river, Gígjukvísl. As a consequence, little water now flows under the bridge over Skeiðará, Iceland's longest bridge (Fig. 24.4). Incidentally, when the bridge was designed in the early 1970s, future changes in the course of the river were expected, and as a consequence the bridge is composed of mobile elements.

Recent warming has also impacted the fauna and flora of Iceland, tree limits are now found at higher altitudes than before, and the productivity of many plants has increased. In agriculture, grain production has increased in the last two decades, and work on soil conservation and forestry has benefited from warming [4]. In the ocean, there have been significant changes associated with warmer sea surface temperatures. Several new species of fish have expanded their range into Icelandic waters, and Icelandic stocks that traditionally were mostly found along the south coast of Iceland have expanded their range to the north coast [4]. As an example of the social consequences of warming impacts, Atlantic mackerel can now be found in significant quantities in Icelandic waters, leading to a commercial mackerel fishery in Iceland since 2006. This has led to an international dispute between Iceland and the EU over fishing rights and quotas.

24.3 Climate Change Projections

Based on the results of the climate models used in the IPCC AR4 report (2007), warming is projected to continue in the twenty-first century. Model results were averaged over the domain covering Iceland and the surrounding oceanic area (60–70°N and 10–30°W) and projected changes are summarized in Fig. 24.5. The warming rate differs among the IPCC SRES emission scenarios [7]. In the warmest scenario (A2), the warming rate is 0.28°C per decade, yielding 2.4°C warming from 2008 to the end of the twenty-first century; in the coolest scenario (B1), the warming rate is 0.16°C per decade, yielding a warming of 1.4°C by the end of the century. The intermediate scenario (A1B) yields a warming rate of 0.23°C per decade and a warming of 2.0°C by the end of the century. In all cases there is a significant spread in the model results.

The warming in Iceland exhibited in the IPCC climate models is somewhat slower than the warming rates observed in Iceland in recent decades. This fits with the view that the recent warming is in part a local natural temperature change, superimposed on a large-scale global warming signal.

Natural climate variability, while considerable (Fig. 24.2), will not overwhelm the projected long-term warming during the century. However, because of natural variability the warming is likely to be uneven, with the climate exhibiting rapid warming during some decades and little or no warming in other periods. With respect to adaptation (see further discussion in Sect. 24.5), it should be noted that this implies that any adaptation strategy must take climate variability into account as well as the projected climate change.

Projected changes in precipitation were estimated using the same climate models (Fig. 24.6). Precipitation is projected to increase on average by 5%. Precipitation is more variable in the climate models, and the spread in the results is consequently large. Nevertheless, in general, precipitation increases roughly in proportion with the warming (Fig. 24.7).

Comparing the projected warming and the increase in precipitation reveals that the precipitation increases by about 2.5% for each degree of warming (Fig. 24.7). Note that this percentage increase is lower than that seen in observations in Iceland from the twentieth century (which are 4–8% per degree of warming). This is possibly a reflection of model biases [4].

The projected warming in Iceland is likely to result in a reduction in the number of frost days and more frequent heat waves. Based on twentieth century records, the duration of snow cover in the lowlands in Iceland is reduced by 3–4 weeks for each degree of warming.

Climate model projections do not show a significant change in wind near Iceland. There are some indications that average wind speed may be reduced along the south coast and increased along the north coast, but the agreement among models is too poor for definite conclusions to be reached.

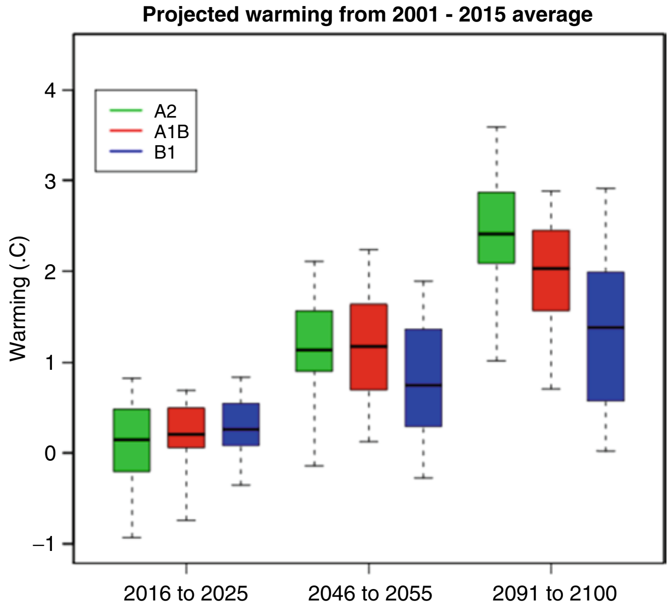

Fig. 24.5 Estimated warming in Iceland for three periods in the twenty-first century. Shown are results based on IPCC models for three SRES scenarios (greatest warming: A2, intermediate: A1B and least warming: B1). The model results were averaged over the domain covering Iceland and the surrounding oceanic area (60–70°N and 10–30°W). In each case, 50% of results lie within each box, and 90% within the range spanned by the lines. The *thick horizontal line* in each box is the average of all models

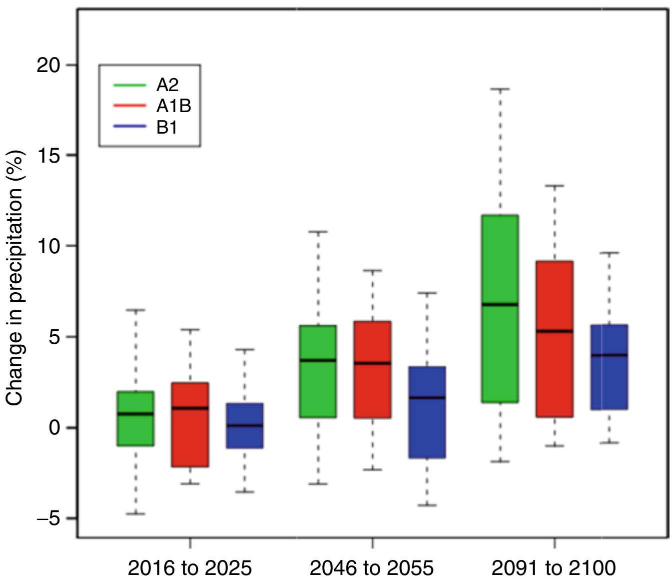

Fig. 24.6 As in Fig. 24.5, but for precipitation

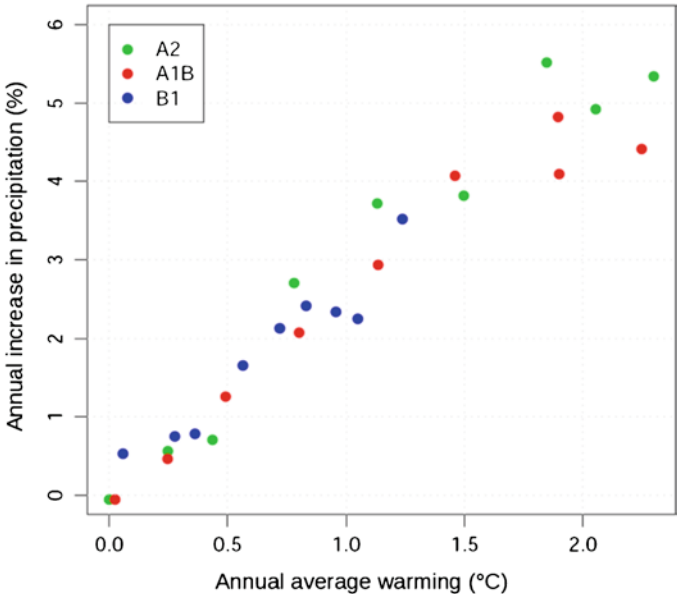

Fig. 24.7 Change in temperature vs. change in precipitation in the twenty-first century in Iceland. Shown are 10-year averages of temperature change and precipitation change (from 2016 to 2025, 2026 to 2035, etc). As in Fig 24.5 the baseline is the 2001–2015 average

24.4 Some Projected Impacts

Extensive modeling has been carried out to examine the impacts of the warming on the glaciers of Iceland. The projected warming is likely to cause a pronounced retreat of glaciers in Iceland [6]. Figure 24.8 shows examples of modeling results for the Langjökull and Hofsjökull ice caps and the southern part of the Vatnajökull ice cap. The figure shows that these glaciers may essentially disappear over the next 100–200 years. By the end of the century Langjökull, the second largest ice cap in Iceland, is projected to have shrunk to 15% of its size in 1990. The projected retreat is not as large for glaciers that are at a higher altitude, such as Hofsjökull and Vatnajökull, but by the end of the century they are still likely to lose at least half their 1990 volume.

Magma production underneath active subglacial volcanoes in Iceland may increase as a result of glacier melting. Modeling of the consequences of the recent retreat of Vatnajökull indicates that due to pressure changes underneath the glacier, the mantle melting rate may increase by up to 1.4 km^3 per century [8]. For comparison, during the relatively large subglacial Gjálp eruption at Vatnajökull in 1996, the amount of lava produced was 0.45 km^3. Thus, volume production change corresponds to about one such eruption every 30 years. The increase in magma production rate may result in more frequent subsurface magmatic intrusions, or if the magma reaches the surface, more frequent or larger volcanic eruptions in the area.

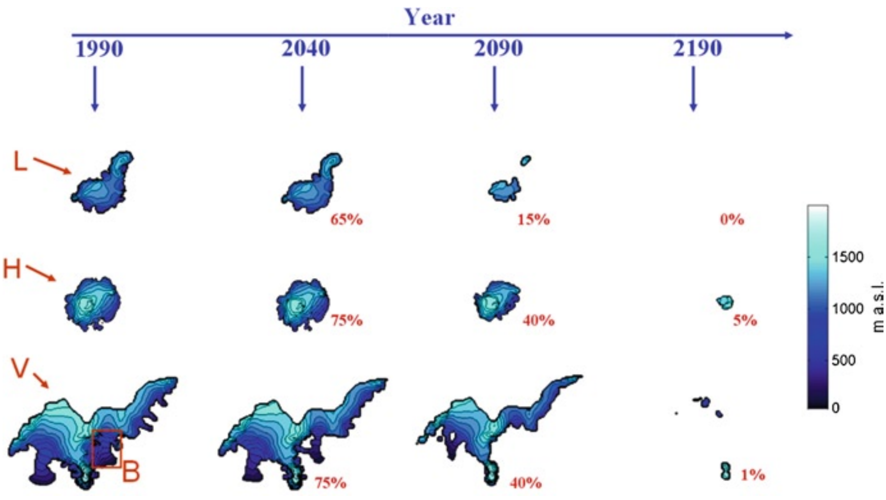

Fig. 24.8 Response of Langjökull (*L*), Hofsjökull (*H*), and Southern Vatnajökull (*V*) to a climate warming scenario. The outlet glacier Breiðármerkurjökull on the south flank of Vatnajökull is indicated with a rectangle marked *B* in the leftmost map of Vatnajökull. The inset numbers are projected volumes relative to the initial stable glacier geometries in 1990. Note that Vatnajökull is only modeled south of the main east-west striking ice divide [6]

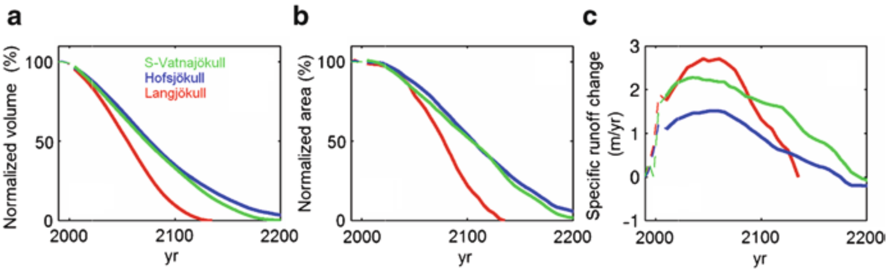

Fig. 24.9 Volume and area reduction, normalized to present day values, and area averaged runoff change. The runoff consists both of glacier melting and precipitation. Initially, enhanced glacier melting is the dominant contribution to runoff change [6]

As the glaciers melt, runoff from them is projected to increase [6]. This can be seen in Fig. 24.9, which shows the changes in volume, area, and runoff for the three glaciers in Fig. 24.8. Due to thinning, the volume of the glaciers initially declines faster than area resulting in fast runoff changes in the next few decades. By 2030, runoff will increase by about 30%. Thereafter, the runoff increase will slow down due to a reduction in glaciated area; peak runoff is expected to occur in the latter part of the twenty-first century.

Although glaciers and ice caps in Iceland constitute only a small part of the total volume of ice stored in glaciers and small ice caps globally, studies of their sensitivity to climate changes have a general significance because these glaciers are among the best monitored glaciers in the world. Field data from glaciated regions in the world are scarce due to their remote locations and the difficult and expensive logistics associated with glaciological field work. Results of monitoring and research of Icelandic glaciers are therefore valuable within the global context, in addition to their importance for evaluating local hydrological consequences of changes in glaciated areas in Iceland.

Concomitant with the projected warming, further changes in biota are likely. The enhancement of plant productivity and upward displacement of tree limits is likely to continue. The impact on marine life is more uncertain, not least due to insufficient knowledge of the long-term consequences of the acidification of the oceans.

Impacts of projected climate change are likely to touch all sectors of Icelandic society. Projected increases in hydropower potential, along with enhanced plant productivity, will affect the resource base of the country, while increased risk of flooding both from rivers and rising sea levels will influence planning and civil response. Because it is likely that there will also be impacts that are not presently anticipated, decision makers must be equipped to deal with uncertainties in impact projections.

24.5 Adaptation Planning

Climate change will inevitably impact most economic sectors, but in general, the magnitude of the impacts is uncertain. This uncertainty derives from several sources. First, the magnitude of the eventual climate change is subject to future greenhouse gas (GHG) emissions, presently unknown, and, second, even were these known, the response of the climate system (the sensitivity of climate to changes atmospheric GHG concentrations) inevitably has some uncertainty associated with it. Finally, the sectoral impacts from a given magnitude of climate change will also have an uncertainty range associated with them. A consistent adaptation strategy will therefore have to take into account the uncertainty in the forcing (GHG emissions), in the response (the climate sensitivity), and the impacts.

Furthermore, when it comes to planning adaptation to climate change, the uncertainty in the magnitude of the impact is not the only issue to consider; the vulnerability and adaptive capacity of societal systems must also be taken into account. In the WGII report to the fourth assessment (AR4) of the Intergovernmental Panel on Climate Change (IPCC) it is pointed out that the formulation of an adaptation strategy must also consider various technical and socioeconomic barriers to adoption [1]. A recent EU report points out that the adaptive capacity is often neglected in adaptation studies and stakeholder contribution is emphasized as an essential part of a successful strategy [10]. Another recent report [9] proposes guidelines for adaptation strategies and among those are stakeholder involvement, flexibility to deal with uncertainties, prioritization of adaptation options, and the preferred use of existing structures and processes. A strategic framework that encompasses all these requirements is mentioned in the IPCC report, which also discusses cases where the adaptation strategy is formulated as a part of a comprehensive risk management strategy.

It is argued here that the problem posed by the uncertainty and the need for flexibility outlined above means that a risk analysis and management viewpoint is especially apt.

In Iceland, there is a need to better quantify the magnitude of impacts and assess the probability of significantly adverse outcomes. To this end, further monitoring, systematic attribution, and enhanced modeling, both of regional climate change and also of likely impacts, will be required.

Climate change impacts on infrastructure sectors are the subject of ongoing studies. While the results of these studies show that significant impacts can be expected plans for adaptation to climate change are in most cases not well developed. The most notable exception is the Icelandic Power Company; the likely impacts of expected climate change are taken fully into account in its operational strategies and investment planning.

Following recommendations from a 1992 report on expected sea level rise, consideration has been made for this in the design of new harbors in Iceland. However, recent studies indicate that sea level rise may far exceed earlier expectations.

There is already substantial experience in Iceland in dealing with risk management of natural hazards, and existing frameworks can be adopted to deal with some climate risks, such as possible increases in extreme weather, flooding, and volcanic eruptions. To deal with impacts that are not related to singular events but rather affect the background conditions of natural and societal systems, policy makers will need different methodologies and frameworks. Examples of these kinds of impacts include slow changes in river runoff that may necessitate changes in the management of energy and water resources.

Capacity building to meet these challenges is ongoing. Some of that will take place in concord with the Global Framework for Climate Services proposed by policy makers at the third World Climate Conference (WCC-3) [11]. The framework is supposed to:

> …bring together developers and providers of climate information, predictions and services, and the climate-sensitive sectors around the world [..] to help the global community better adapt to the challenges of climate variability and change.

The development of risk management frameworks and their implementation is likely to be an extended endeavor that requires intensive international collaboration between different fields of science and engineering. Recognizing and responding to the risks and opportunities posed by climate change will be a challenging task for scientists and policy makers alike.

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Part V
Inland Applications

Chapter 25
Adaptation of Inland Systems to Climate Change with Challenges and Opportunities for Physical, Social, and Engineering Disciplines*

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Abstract This paper explores several issues associated with the adaptation of inland systems to climate change, particularly by addressing the vulnerabilities of inland centers of people, industry, and agriculture that are interconnected at multiple temporal and spatial scales. The aim of the paper is to improve understanding needed for sustainable climate change adaptation of inland systems, where sustainability encompasses social and psychological adaptation, environmental justice,

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and the preservation and enhancement of human dignity and natural resources. This requires participatory approaches with iterative problem framing and solution generation that are respectful of both human dignity and the integrality of nature. A vital component of developing adaptation strategies is the assessment of current vulnerabilities, namely the extent to which current climate variability and change, acting together with other stressors, impact inland systems. This assessment requires an understanding of the climate system and its impacts to inland systems, as well as the responses of the systems to changing climate. A complex adaptive systems approach can be useful in carrying out such an assessment. Important factors include how inland centers – especially marginal lands, disadvantaged populations, and threatened ecosystems – are resilient to both episodic shocks and to steady trends, which may be difficult to measure, monitor, or forecast. Climate change adaptation strategies for inland systems must also take into account transboundary issues, and take advantage of opportunities where present.

25.1 Introduction

Inland systems, defined as those not directly affected by sea level variations and other oceanic processes such as hurricanes, present unique vulnerabilities to climate change. The range of inland system components vulnerable to climate changes includes water quantity and quality, demographic and socioeconomic conditions, ecosystems, fires, land use changes, soil moisture, erodibility, and productivity. Inland systems are pressured by climate impacts to coastal regions. For example, rising sea levels may alter the range of saltwater intrusion, affecting aquatic habitat suitability and groundwater quality for drinking water [25–27]. Migrations of people and industries, flows of resources and energy, and other adaptations of inland systems will be unique to the local and regional conditions, but there may be common elements [24]. Social/psychological adaptation, environmental justice, and the preservation and enhancement of human dignity and natural resources will be essential features of sustainable adaptation of inland systems [7, 9, 21, 39].

The authors of this paper participated in a workshop of engineers, physical and social scientists and policy makers convened in Hella, Iceland, in June 2010 to address systems adaptations to climate change. The paper highlights several of the challenges and opportunities of adaptation of inland systems from a perspective of multiple disciplines.[1] The group discussed the various national strategies responding to major climate events such as the dust bowl catastrophe in the 1930s – how the planting of 220 million trees as wind barriers was a failed strategy, yet soil conservation districts are in use to the present day.

After a discussion of climate-related issues affecting inland systems, a description of the major changes to be expected in the inland territories under climate

[1] Another two groups at the workshop addressed coastal systems and military systems.

change is presented. It is also important to assess how historical inland territories have been occupied and developed over time. We then describe a range of adaptation approaches, namely interventions on the changing threats and opportunities, new and not-so-new but nevertheless effective. Such description also includes a discussion on how to combine top-down (technically scientific) with bottom-up (stakeholders) diagnosis and solutions. We hereby submit our analysis of the implications of potential climate change to inland systems and our humble recommendations for future options for adaptation of these systems with attention to the sustainability and emergence of communities, addressing the primacy of human dignity and partnership with nature.

Several themes of particular significance from the workshop are addressed in this chapter: How can we more surely identify the universe of effects; e.g., wildfires, variability of rainfalls? What are the relevance and lessons learned of trans-boundary issues and transfers? What are the greatest science and technology and other capability/knowledge gaps for adaptation of inland systems? How best to characterize the significant interactions between sciences, societies, communities, individuals, the public sector, and the private sector for adaptation of inland systems? How might we frame an approach to climate change adaptation for inland systems?

25.2 Framework for Understanding Climate Change Impacts to Inland Systems

In order for adaptation to climate change to be effective, it is vital to be aware not only of the projected changes in the local climate but also of how the current climate and other stressors such as land use, urban development, land cover, and socioeconomic conditions impact inland environments, infrastructure, and human activities. Indeed, climate has been, is, and will continue to be, variable on all time scales, regardless of whether human activities have interfered with that variability.

The recent decades have been, by and large, not only benign from the perspective of economic development in most, if not all, northern countries, but of relatively limited climate variability. Analyses of historical climates suggest that such benevolent and restrained climate variability did not exist throughout the last millennium, or even through recent decades in parts of the developing world. Yet ample evidence exists to suggest that many planners, in many sectors, and in numerous countries around the world, have been lulled into a false sense of security, and continue to draw plans based on the assumption that climate is stationary and that designs suitable under the favorable climate of recent decades will continue to be appropriate in the future. The European heat wave in 2003, Hurricane Katrina in 2005, and the Queensland flooding in 2011 have proven that under current climate conditions, even supposedly prepared developed-world societies can be caught off guard. The global economic collapse of 2008 is another example of how abrupt changes can expose vulnerabilities of human and governmental systems.

Thus, a vital component of adaptation strategies is the assessment of current vulnerabilities, namely the extent to which current climate variability (and extremes) impact inland systems. In order to carry out such an assessment, adequate climate information, in the form of, e.g., long-term records of climate variables with sufficient detail to extract relevant statistics, must be accessible. Having established the proper climate information, several processes might need to be undertaken in order to manage climate risks either in specific sectors or in a more holistic fashion:

- Climate Risk Assessment (CRA): an assessment of the vulnerabilities/risks posed to an infrastructure/societal sector/project by weather and climate variability that might include:
  - Impacts of adverse (or favorable) weather, such as storms and floods
  - Impacts of adverse (or favorable) climate variability, including droughts
  - Long-term impacts, positive and negative, associated with climate change
- Climate Risk Management (CRM): proactive management aimed at mitigating the impacts of climate variability and change, based on a CRA and using all available information, including predictions on all time scales.
- Climate Proofing: actions taken to lessen, or perhaps eliminate, the potential negative impacts due to climate variability and change based on a CRA and on CRM principles.
- Environmental Impacts Assessment (EIA): an assessment of the impacts on the environment *in toto* of an infrastructure/societal sector/project during its entire life cycle, including on the ground, on the scenery, on the atmosphere, on flora and fauna, and on society.

Inland systems clearly span a wide variety of sectors – such as agriculture, infrastructure, transport, energy, health, and ecosystems – all affected to some extent by climate variability and change. Obviously it is a colossal task to tackle all these sectors at once, not least because their intrinsic planning time scale can vary considerably, from the shorter scales in, say, health planning, to much longer scales for infrastructure. In this paper we look for similarities in how sectors might be affected by climate variability and change. These two will be discussed separately to start with and then together so as to provide options for a more integrated approach to climate adaptation.

Specifically, infrastructure and energy should be analyzed according to the following steps:

- Identify what is known about vulnerability and impacts of climate change at local/regional scales.
- Consider other system stressors and how they interact with changing climate.
- Define the role of risk analysis in managing risks posed by climate change.
- Define the applicability of adaptive management for climate change.
- Identify strategies that developing countries can use to manage security risks associated with climate change and other stressors.
- Identify specific research needs for improving the value of risk analysis as applied to climate change.

25.3 Complex Adaptive Systems and a Multidisciplinary Workforce

All water management decisions must be made under conditions of uncertainty and complexity. Many factors endogenous and exogenous to the specific management area of interest impact the decision – natural and urban areas function as complex adaptive systems. Consequently, management decisions should be based on a systems approach for flexibility and sustainability. This condition requires multidisciplinary research and a holistic approach to develop an integrated set of tools that can be used within a deliberative and adaptive decision-making process.

Changing climate exacerbates uncertainty and expands the bounds of the system both in spatial and temporal terms. NOAA and EPA commissioned a recent National Research Council report, *Informing Decisions in a Changing Climate* [10]; it states explicitly that our current decision-making processes and institutions are not adequate to deal with changing climate. This challenges scientists, engineers, politicians, planners, managers, and citizens to develop and implement new tools, processes, and institutions to inform water management decisions in a changing climate. This same report states that a multidisciplinary work force of biophysical scientists, social scientists, and engineers whose members work together as a team is necessary to provide better information for use by decision makers.

25.4 Human Dignity and Capacity for Adaptation to Climate Change

Why is it essential to include people in adaptation planning and how do we include them? International treaties are being negotiated to encourage and enforce climate change mitigation through control of emissions of greenhouse gases. Now, there is recognition that the current levels of greenhouse gases in the atmosphere have already committed the Earth to differing degrees of change over the next 100 years or more As a result, international and national organizations are developing protocols urging adaptation to climate change. Though mitigation and adaptation efforts are currently loosely coupled, there is growing realization that effective use of resources requires integration of adaptation and mitigation.

Current treaties and protocols around climate change adaptation are insufficient and difficult to implement and enforce. Though climate changes may be global and regional in nature, most adaptation is local and requires community planning and grass roots movements. Collective action, at all scales and levels of governance and society, is needed to address the impacts of climate change to achieve sustainable societies and ecosystems. An essential and critical part of this premise is recognizing the dignity of all people and the imperative of representing the wide range of interests, insights, knowledge, and experience that resides in a highly diverse society. Disadvantaged groups and communities are being disproportionately affected by the impacts of climate change (for example, submergence of the Sundarbans and Pacific island nations, and the effects of Hurricane Katrina). These groups and communities must be intimately included in developing adaptation strategies for society to survive changing climate.

Water management problems under a changing climate represent a class of problems called "wicked." Wicked problems, formally defined in 1973 by Rittel and Weber, are those problems that cannot be solved by technology and science alone because they have a social and human element. Because of this, it is necessary not only to tackle wicked problems with a multidisciplinary, integrated work force but also to engage citizens in the process of data collection, analysis, and decision making. In the consensus-building field, this is called joint fact finding. Public participation processes are particularly useful for addressing very complex and contentious environmental issues. Well-designed public participation processes have been effective for developing sustainable solutions to vexing environmental problems [10] and hold promise as a way to better inform decisions under changing climate [10].

Decisions in a public engagement context are often based on values and these values play out in a dynamic fashion as part of the decision processes [28]. Values differ among cultures and within cultures. Moreover, different values and value sets are weighted differently in different contexts and situations. We need to take into account this range of values to adapt to changing climate; this may require a transformation in governance, which in the U.S., at least, is dominantly based on values of power and wealth. Citizens will lead the way as they have for all transformational movements. Governments will respond by enacting laws. We need to develop a process to learn from each other as different cultures and governance systems will respond to the challenges of climate change in diverse ways.

25.5 Modeling the Climate System and Its Impacts to Inland Systems

Numerous climatic processes affect inland social and economic structures in important ways at all time scales. Such climatic processes can be subdivided into those pertinent to the atmosphere, hydrosphere, cryosphere, and biosphere. *Atmosphere* defines the changes in circulation processes and manifested in variables like temperature, humidity, pressure, winds, precipitation, and cloudiness with marked impacts on living conditions for inland systems. The *hydrosphere* is crucial to activities such as transportation of humans and cargos by river and lake routes. Rivers and lakes are sources of fresh water – a vital factor for sustaining life in inlands and the subject of serious concern for mankind. The *cryosphere* strongly affects the development of essential parts of inland systems in some extratropical regions. Changes in permafrost may lead to vital losses for inhabitants of vast inland areas. For instance, more than 60% of Russia's territory is permafrost, and most current construction and communication infrastructure are oriented to permafrost boundaries that existed in previous centuries. Crucial negative effects for the inland structures may result from permafrost melting. The *biosphere,* which includes both flora and fauna, is also an important factor in detailed and thorough consideration of inland systems, insofar as it defines many aspects of human existence, including health, food, and recreation, as well as the development of industry and agriculture.

Not only the origin of processes in the climate system, but their time scale is essential for inland structures. All changes in the climate system are superposition of many processes that manifest themselves on time scales which vary from seconds to decades and centuries. Clear understanding of time scales of processes is an indispensable factor in working out decisions for adaptation to climate changes.

Temporal variability in the climate system should be considered in conjunction with spatial variability; first of all, with horizontal variability. For inland systems, the geographical variability of climate is larger than, say, that for countries surrounded by sea or oceans. Therefore, all these affects on the inland structures (influences of various parts of Climate System components), as well as modes of temporal and spatial variability of these processes, need to be taken into account when adaptation decisions are planned and recommended.

Observational data are crucial for making any recommendations when decision processes are undertaken. Their value increases as the quality and length of observation periods (i.e., length of time series), and as the responsibility for each recommendation related to climate changes and the responsibility for possible adaptation and mitigation decisions also increase.

Humankind has huge collections of observational data, most of which are measured just in inland territories. It is easier to make denser and more regular observations on land than over ocean. For example, global national meteorological services manage surface observations on more than 8,000 stations. They include observations for coastal territories as well, but the observational/measuring routines for all of them are identical and are under control of international agencies.

It is important to address the following questions (contained in IPCC Assessment Reports). These questions, among others, are: "is climate becoming warmer?" and "is climate becoming more variable and more extreme?" To answer the first of these questions, it is, in general, enough to estimate some changes in the average state of climate (say, decadal changes in annual or seasonal mean temperature). However, to answer even this first (and more simple!) question, it is better to study what happens with the whole distribution of measured values, because mean value is just one of many characteristics of distributions. We avoid the limitation of solely estimating mean values when we try to answer the second question; i.e., "is climate becoming more variable and more extreme?" In this case, it is better to analyze the evolution of the whole distribution, because – as is known from statistics – distributions carry the most complete information on what happens with our measured magnitudes.

Immediate modeling needs include access to observational data with temporal regularity, a long period of observations, and high temporal resolution. These conditions are indispensable for making reliable assessments of changing climate, preparing adaptation recommendations, and validating climate models that subsequently will be used for projection of future climate change.

25.6 Responses to Climate Change in Inland Systems

One of the fundamental challenges that climate change poses is testing the limitation of human ability to deal with change. Climate change increases the complexity of identifying the range of impacts, the nature of interactions with socioecological systems and the magnitude of consequences of the impacts (in terms of scale, location, timing, and frequency). While change is both dynamic and a constant of human societies [4], there is a growing consensus that the rate of change that society is increasingly facing is unprecedented [3, 8]. During the last 50 years, human activities have modified ecosystems around the world more rapidly and more extensively than any other time in human history [8, 29, 36]. This has resulted in unpredictable qualitative changes in the behavior of ecosystems. Coupled with the complexity of social systems, this results in increasing uncertainty and potential for surprise.

Since the 1980s, the concept of risk has become central to the explanation of changes and challenges in modern societies, particularly in the relation between society and its natural environment [2]. Researchers recently pointed to the limits of the notion of risk as it has been used since the 1980s [5, 12, 18]. Furthermore, there is a recognition that current institutions and policies designed around a linear understanding of change and risk are not adequate for dealing with current rates of change. A potentially more useful approach would be to design our policies around explicit recognition of the unknown and build in flexibility, mechanisms for learning, and adaption in these policies. One potential way of differentiating the unknown is as follows:

1. Uncertainty, where the range of possible outcomes is known but probabilities cannot be assigned.
2. Ambiguity, where incommensurable priorities or notions of harm prevail.
3. Ignorance, where neither outcome nor likelihoods are known.
4. Fundamentally new, inexperienced – surprise [13, 19, 20, 23, 34].

These unknowns can turn into crisis when they reveal an unambiguous failure of policy [23].

Response to change can range from short-term superficial adaptations to reduce vulnerability to the long-term, more fundamental changes that may be necessary for ensuring sustainability. Response can be reflexive (spontaneous, automatic, not thought through) or reflective (strategic and planned) [2]. The nature of change or perturbations that the systems of interest are going through can be broadly divided into stresses and shocks [14]. Stresses may be gradual, not very visible, and therefore easy to ignore. An example of this in climate change context would be increased temperatures, rising sea levels, soils erosion, and melting glaciers. Shocks, on the other hand, have heightened intensity leading to increased impacts; for example, failure of critical infrastructure due to increased extreme weather conditions.

Several conceptual frameworks have been developed for responding to change. For example, diversification (as in an investment portfolio) is a universal strategy aimed at reducing risks; it increases options for coping with shocks and stresses, making the systems less vulnerable [3]. Building resilience into socioecological systems, as Tompkins and Adger [41] suggest, is an effective way to cope with unknowable risks. Resilience is a forward-looking concept that provides a way of thinking about policies for future environmental change, "an important consideration in a world characterized by future surprises and unknowable risks" [3]. The STEPS pathways approach distinguishes four possible kinds of strategy to deal with change: control to address short-term shocks (stability) or long-term stresses (durability), and response to shocks (resilience) or stresses (robustness) [34]. Lilia Yumagulova further expands on conceptualizing change and responding to it in another chapter in this volume.

25.7 Transboundary and Other Regulatory Experience with Climate Change and Inland Systems

Climate impacts and their resulting vulnerabilities cross political boundaries in the same way as do existing socioeconomic stressors and natural events such as floods, droughts, coastal storms, fires, invasive species, economic crises, and social unrest. Because climate change "threatens the basic elements of life for people around the world – access to water, food, health, and use of land and the environment" [37], it could be considered to be a stressor likely to increase transboundary tension or conflict. However, it can also provide an opportunity to make "use of an 'open moment' – a rare period in which the status quo can be ruptured and possible futures imagined" in the words of Ghani and Lockhart [15]. Though they referred to the planning and implementation of the Marshall Plan in the period of post-World War II Europe, global involvement in the IPCC and growing recognition of the potential threats posed by climate change could lead to a similar open moment for transboundary adaptation measures. Taking advantage of this open moment might be the method by which nations facing a "potential downward spiral can be transformed into a virtuous circle" though the cooperative actions of governments and institutions [35]. They offer 12 recommendations, including supporting good governance, developing national adaptation plans, engaging the private sector, linking international action frameworks, and promoting regional cooperation for adaptation.

An example of transboundary cooperation already exists in the realm of water resources management.[2] Though water-related conflicts are well known [16, 17], Wolf et al. [41] report that transboundary cooperation far exceeds instances of acute transboundary conflict. While screening methods have been used to identify areas where climate change-related vulnerabilities might result in conflict over water [1, 22, 41], studies also indicate that there is no pattern of impact by climate on

[2] See the Transboundary Freshwater Dispute Database at http://www.transboundarywaters.orst.edu/database/ for up-to-date information.

water disputes [41]. In fact, societal and institutional actions relating to the governance of water are an important factor in conflict [32, 33] that can help to alleviate impacts [22, 30]. Rakin [31] discusses the central role of transboundary cooperation with respect to two case studies (Central and South Asia), recommending that early action be taken to forestall critical situations. Delli Priscoli [11] sees adaptation actions related to water as key s to social resilience and stability. White et al. [40] propose that:

> …water resources managers, if adequately prepared, are uniquely positioned to provide both adaptive capacity through operational, demand management, and infrastructure changes [6] and mitigation capacity through innovative power generation and emission control strategies.

25.8 Summary and Needs for Future Work

Our approach in this paper has considered that adaptation of inland systems should take into account the interdependencies of climate change impacts and responses, including trending and episodic phenomena; economic mechanisms; and concepts of sustainability supporting human and natural systems. The sustainability and adaptive management of inland systems must include a thorough knowledge of both impacts and responses to climate change. A complex adaptive systems approach that emphasizes the human role in adaptation as well as the physical manifestations of climate change and response is likely to be effective in developing adaptation strategies, especially for transboundary situations. Related topics for exploration include societal behaviors in inland systems, including societal adaptation and social change, identification of thresholds of capacity and resources for sustainable inland systems, and the roles of episodic versus regular or trending changes.

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Chapter 26
Influence of Climate Change on Reservoir Water Quality Assessment and Management

Effects of Reduced Inflows on Diel Ph and Site-Specific Contaminant Hazards

B.W. Brooks, T.W. Valenti, B.A. Cook-Lindsay, M.G. Forbes, R.D. Doyle, J.T. Scott, and J.K. Stanley

Abstract Climatic changes are commonly recognized to alter freshwater ecosystems. This chapter provides a unique perspective on the implications of climate change for reservoir inflows, water quality assessment, and management of aquatic contaminants influenced by site-specific pH. The various physical, biological, and chemical dynamics of reservoir zones are reviewed and a case study of four reservoirs in Texas demonstrates that reduced inflows and daily pH variability have direct implications for the collection, analysis and interpretation of water quality data. The chapter concludes with recommendations for reservoir water quality assessment and management, particularly given the prospect of increased frequency and duration of drought conditions in the southwestern and south-central U.S.

26.1 Introduction

Climatic changes are commonly recognized to alter the structure and functions of freshwater ecosystems [18]. In fact, a recent special issue of *Limnology and Oceanography* focused on lakes and reservoirs as sentinels [1], integrators [68], and

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regulators of climatic change [127]. From impacts on shortening ice cover [117] to increased risks from harmful algal blooms [91, 100, 136] and anthropogenic contaminants [7, 63, 75, 87], understanding the implications of climate change on environmental assessment and management is critical [104, 141].

Climate change can result in strong shifts in precipitation patterns that alter instream flows [4, 8]. Cayan et al. [16] recently projected sustained periods of drought for the twenty-first century in the southwestern U.S., which will challenge water resource management efforts [47, 74]. In fact, drought conditions occurred during late 2005 and 2006 in Texas, resulting in elevated temperatures, reduced precipitation and decreased freshwater inflows to reservoirs. In Sect. 26.5 of this chapter we present a case study of the influence of drought on instream flows, reservoir pool levels, and implications for site-specific environmental assessments. Similar increases in temperature and decreases in precipitation, inflows, and reservoir pool levels have been observed [22, 78] and predicted elsewhere [92] during summer and autumn months. Our previous efforts in Texas reservoirs focused on developing an approach to support water quality assessments in different reservoir locations during drought conditions [11]. We further highlighted the importance of impoundment and sampling location depth during studies of reservoir carbon and nitrogen dynamics [40, 41, 108]. Valenti et al. [133] identified the importance of such drought conditions on reduced instream flows, diel pH variability, and resulting site-specific uncertainty associated with aquatic risk assessments of ionizable contaminants.

In this chapter we provide a unique perspective on the implications of climate change for reservoir inflows, reservoir water quality assessment and management of aquatic contaminants influenced by site-specific pH. Understanding these relationships is critical given the recent linkage among El Niño Southern Oscillation to decreased inflows and decreased dissolved oxygen levels in a reservoir near Barcelona, Spain [78]. Thus, an objective of this study is to explore how reduced inflows to reservoirs can influence site-specific hazards of aquatic contaminants. Before we do so, however, it is important to first recognize that the unique hydrology of reservoirs classifies them as intermediates between river and lake ecosystems [64]. Therefore, we begin with a review of the effects of reservoir inflows on the physical, chemical, and biological factors that influence reservoir water quality. We then provide a case study that emphasizes the impacts of drought and reduced reservoir inflows on pH-related contaminant hazards to aquatic life.

26.2 River and Lake Hybrids: The Importance of Considering Reservoir Zones

Early investigators knew that reservoirs differed from lakes and detailed the measurable physical, chemical, and biological gradients that developed along the axis of impoundments [5, 48, 60, 102]. Similarly, stream ecologists have documented impoundment effects on the hydrology, chemistry, and biology of downstream and upstream systems [138, 139]. Focusing on this early descriptive work, Thornton et al. [122] proposed a heuristic model of reservoir zonation based on morphology (width and depth), hydrology (flow velocity and turbulence), and sedimentation rates. The model described three reservoir zones—riverine, transition, and lacustrine—that respectively exhibit decreasing downgradient advective energy associated with turbulence from river inputs. The zonation model proposed by Thornton et al. [122] remains the most widely used descriptor of reservoir spatial patterns, although locating reliable boundaries between riverine-transition and lacustrine zones has remained a challenge [40]. Not surprisingly, this reservoir zonation model has been expanded in numerous reviews to include a variety of other limnological characteristics (Table 26.1).

Numerous authors have used Thornton's heuristic model as a basis for interpreting observed gradients in water quality parameters. Allochthonous inputs from watersheds are often major sources of nutrients to a reservoir; thus, riverine zones are generally high in nutrient concentrations, particularly during higher inflows [61]. The influence of the watershed on up-reservoir water quality is also evident from increased turbidity due to suspended sediment loadings of allochthonous organic matter [124] (Table 26.1). These patterns are exemplified in a study by Pickett and Harvey [94] that demonstrated decreasing total nitrogen and phosphorus concentrations and increasing Secchi transparency along the longitudinal axis of a South Carolina reservoir. Similarly, Doyle et al. [24] observed decreased turbidity along the riverine-lacustrine gradient of Lake Waco, an impoundment in Texas.

The deepening and widening of reservoir basins often causes a dissipation of advective energy in the water column and increases in the sedimentation of fine particulates [125]. These trends result in the development of transition zones with increasing water transparency. The reservoir basin eventually deepens and widens to a point of maximum volume, where advective energy due to river inflow is minimized and water transparency is maximized (Table 26.1). Within the lacustrine zone, advective nutrient input is minimal and nutrient cycling is dominated by internal processes [61]. Mean chlorophyll *a* concentrations respond to such transparency gradients along the reservoir gradient. Specifically, water column chlorophyll *a* values have been shown to be relatively low in the riverine zone and then increase significantly in the transition zone before again falling in the lacustrine region [65]. A decreasing trend in particle-associated parameters (total Kjeldahl nitrogen, total phosphorus, ammonium, and total iron concentrations) along the riverine-lacustrine gradient has been reported for seven Kentucky reservoirs [20]. Filstrup and Lind [35] recently defined similar sedimentation patterns and quantified sediment resuspension along the riverine-lacustrine continuum in Lake Waco, Texas.

The dynamics of biological communities have also been explored in the context of Thornton's reservoir zonation model. Although relatively high levels of available nutrients are often present in the riverine zone, primary production is predicted to be low due to light limitation in turbid waters [65]. However, increasing water transparency results in increased phytoplankton production in the transition zone before a subsequent decrease in the lacustrine zone as nutrients become the growth-limiting factor [65]. Buckavekas and Crain [13] demonstrated increasing phytoplankton

Table 26.1 Historical literature descriptions of three reservoir zones proposed by Thornton et al. [122]

Reference	Riverine	Transition	Lacustrine
Kennedy, Thornton, and Ford [59]	Current velocities decreasing, but sufficient to maintain well-mixed environment Short water residence time	Buoyancy forces begin to dominate Inflow plunge point (if present) Upstream and downstream boundary of transition zone = location of plunge point under low-flow and high-flow conditions Zone of sedimentation Most dynamic zone Most diverse zone Increased clarity High NPP High organic matter load ->low DO	Buoyancy forces dominate Inflows move through reservoir in well-defined horizontal layers Thermal stratification well established NPP maintained by internal nutrient recycling Autochthonous > allochthonous
Thornton [124]	Narrow Well-mixed- aerobic Declining but significant advective forces poor light penetration NPP light limited Aerobic despite significant SOD	High sedimentation Increased light Includes compensation point (transition to net autotrophic water column)	low sedimentation of inorganic particulates Higher light penetration NPP nutrient limited net autotrophic mixed layer

Cole and Hannan [17]		Intermediate	Deep
Depth	Shallow		
Velocity	High	Intermediate	Low
Sedimentation	Medium	High	Low
Hypolimnetic volume	Very low	Low	High
Hypolimnetic temperature	High	Medium	Low
Dissolved Oxygen demand	Medium	High	Low
Kimmel et al. [65]	High-flow velocity	Decreasing flow velocity	Longest retention time
	Short retention time	Increased retention time	Low dissolved nutrients
	Increased TSS	Sediments of silts and clays	Low non-algal turbidity
	Increased light ext	Increased light penetration	Deeper Z_p
	Increased non-algal turbididty	"Plunge point"	
	$Z_{mix} > Z_p$ =>light	most fertile region	
Morphology	Narrow	Broader, deeper basin	Deep, lake-like basin
Flow	High-flow	Reduced flow	Little flow
Suspended solids	Sedimentation	Reduced	Low sedimentation
P:R	P<R	Intermediate	P>R

NPP net primary productivity; *SOD* sediment oxygen demand; *Autochthonous* originating within the system; *Allochthonous* originating outside the system; *Net autotrophic* photosynthesis exceeds respiration; *Net heterotrohic* respiration exceeds photosynthesis; *POM* particulate organic matter; *DO* dissolved ozygen; Z_{mix} mixing depth; Z_p depth of the photic zone nutrient limitation and occasional spatial shifts in the nutrient limitation of algal production along a Kentucky reservoir gradient. Some evidence has supported complex seasonal shifts in phytoplankton nutrient limitation status [26]; however, few studies have demonstrated similar spatial complexity [49]. Increased nutrient limitation of near-dam stations relative to up-reservoir locations is commonly [49] but not universally [115] reported. Havel and Pattinson [54] reported strong longitudinal patterns in the densities of algae and zooplankton with cyanobacteria populations being most abundant in up-reservoir and tributary sites in Bull Shoals Lake, Arkansas. More recently, Scott et al. [108] and Doyle et al. [24] identified reservoir transition zones as potential hot spots for nitrogen-fixing cyanobacterial blooms.

Because primary production in riverine zones is relatively low, the ratio of primary production to respiration (P:R) in this zone has historically been believed to be less than 1 (Table 26.1). The trend of P<R is usually considered a formula for anoxia and stress to aquatic life; however, the riverine zone of reservoirs is expected to maintain some degree of oxygen stability through mixing from turbulent energy provided by river inflows. In the transition zone, respiration should remain high but as previously mentioned, primary production is expected to increase, increasing P:R to approximately 1 (Table 26.1). The lack of turbulent energy in transition zones decreases reaeration, which may cause high oxygen demand and large diel swings in dissolved oxygen concentrations [17, 101]. Historically, community respiration is expected to be minimized in lacustrine zones and P:R is therefore predicted to increase to a value greater than 1 (Table 26.1).

Predicted spatial trends in reservoir ecosystem metabolism may not hold true because reservoir age, land use, and reduced inflows impact hydrodynamic and thus biological processes. For example, we recently demonstrated net heterotrophic conditions (P<R) for lacustrine zones of seven Texas reservoirs during low-flow conditions [41]. Such considerations are important because P:R dynamics influence diel dissolved oxygen patterns and the prevalence of anoxic conditions, which are critically important for the protection of habitat for aquatic life. The relationships among P:R, dissolved oxygen, and pH are further explored in Sect. 26.4.

Changes in bacterial communities along reservoir gradients have been less frequently investigated. However, Simek et al. [109] studied the changes in the epilimnetic bacterial community of a Spanish reservoir. They found strong longitudinal zonation of bacterial community composition and food web structure that were driven primarily by hydrology and high localized inputs of river-borne organic matter [109]. Lind [69] suggested that bacterioplankton production may be high in riverine zones due to allochthonous dissolved carbon inputs. Production in the transition zone should also be high, supported by increased production of autochthonous dissolved carbon (Table 26.1). Finally, production in lacustrine zones may be lower because phytoplankton productivity is lower and this zone exhibits higher rates of algal cell loss due to sedimentation. Further, Lind et al. [71] examined data for several reservoirs and demonstrated a consistent increase in trophic states along the riverine-lacustrine gradient. Specifically, riverine zones are expected to be more eutrophic than other reservoir locations, and lacustrine zones should be the least eutrophic [71]. Lind and Barcena [70] showed that storm events can temporarily shift the trophic relationships proposed by Lind [69] as floodwater inflows pass through the impoundment. Again, this perspective may need to be modified as reservoirs age and watershed development occurs, as evidenced by the recent work of McCallister and del Giorgio [80] and Forbes et al [41].

The longitudinal gradients of morphometry, hydrology, biology, and ultimately water quality reviewed above and their responses to inflows and droughts are fundamentally recognized by researchers working in reservoir systems. Because reservoir zones represent uniquely different habitats for aquatic life, Brooks et al. [11] questioned whether water quality criteria and standards should be developed for specific reservoir zones. However, water resource managers, water board and commission members, and the general public are much less aware of the spatiotemporal uncertainties related to quantifying the water quality of a reservoir [71]. Therefore, Lind et al. [71] recommended that reservoir zonation should be considered in sampling, assessment, and reservoir management. In fact, Lind et al. [71] further recommended that the normal changes along the longitudinal gradients should form the basis of a water resource management plan for multiple uses of the reservoir (e.g., aquatic life use, contact recreation, drinking water withdrawals). Additionally, Hobson et al. [56] recently demonstrated the effects of stormwater inflows on longitudinal gradients of natural organic matter and its influence on source water withdrawals for drinking water treatment.

Unfortunately, consideration of reservoir zones and their responsiveness to inflows are seldom integrated in water quality regulatory frameworks in the U.S. For example, in Texas, water quality criteria and standards only exist for water bodies generically classified as either streams or "lakes," even though there is only one naturally occurring lake in the State (Caddo Lake) that is large enough to qualify for water quality protection. Although delineation of reservoir zonation has largely been based on qualitative changes, numerous studies have interpreted their research findings within the framework of Thornton's zonation paradigm. For example, Brooks et al. [11] proposed coupling hydrodynamic modeling with multivariate statistical analyses of physical, chemical, and biological factors to differentiate various reservoir zones or habitats. This approach would allow for site-specific determination of reservoir zone locations as they may be influenced by inflow events and water withdrawals.

26.3 Influence of Inflows on Reservoirs

As previously noted, influences of climate change on river hydrology may have profound effects on reservoir zonation and water quality. Altered inflows can dramatically influence physical, chemical, and biological processes, which may in turn complicate reservoir water quality assessment and management. Reservoir limnologists routinely consider the dynamic nature of reservoir gradients and how inflow variability may cause them to shift in time and space. For example, Wetzel [142] noted that lakes routinely receive inflows from lower-order streams and more diffuse sources because lake watersheds are comparatively smaller than those of impoundments. Thus, reservoirs generally receive a majority of inflows from higher-order streams and rivers associated with larger drainage areas [142]. A number of researchers have commented on the dynamic nature of the riverine and transition zones in particular, noting that these locations have variable and somewhat unpredictable physical, chemical, and biological dynamics. Kimmel and Groeger [64] proposed a view of reservoirs as semi-fluvial environments and pointed out the likely influence of flushing rate or water retention time on the spatial and temporal heterogeneity of these systems. As we examine below, others have likewise recognized the importance of hydrologic flushing and stressed that the reservoir zonation model, while valuable, is likely to vary dramatically in space and time, largely depending on inflow patterns.

The transition zone is clearly recognized as the most dynamic of the reservoir zones [59]. Furthermore, it is widely acknowledged that the position of this zone is subject to substantial fluctuations related to hydrodynamic forces [27]. Under high-flow events, the exchange between a cove and the main reservoir may be dominated by advective momentum of the entering stream. However, for most reservoir tributaries located at lower latitudes in semiarid and arid regions, inflows may be low enough that the advective momentum dissipates rapidly in the lotic system. In Lake Lewisville, Texas, for example, fluctuations of riverine and transition zone locations were related to drought and water withdrawal patterns [120]. Kennedy et al. [59] suggested that the upstream and downstream boundaries of the transition zone may correspond to the location of the plunge point under low-flow and high-flow conditions, respectively. When density of inflowing waters is greater than that of the reservoir surface layer, then water from the inflowing stream will "plunge beneath" the surface layer of the reservoir, resulting in an underflow [42]. However, the position of the plunge point is dynamic and responsive to inflows, reservoir volumes and water column densities. Accordingly, in reservoirs where a plunge point is generally detectable, the boundary between the riverine and the transition zones would be the plunge point under low-flow conditions.

Kimmel et al. [65] discussed the Thornton zonation model and commented on numerous exceptions resulting from the dynamic nature of reservoir zones. For example, they cited evidence of numerous rapidly-flushed, run-of-the-river impoundments where riverine-like conditions persist throughout most or all of the reservoir. Additionally, reservoirs with lower inflows and long residence times had highly compressed riverine and transition zones and likely function as "lakes" over most of their extent, despite changes in morphology in the upstream direction. Changes in reservoir zonation were also observed by An and Jones [3] for a Korean reservoir based on annual monsoon pattern. In years with strong monsoon, there was sharp longitudinal zonation with a turbid, light-limited riverine zone followed by productive transition and lacustrine zones. However, when the monsoon was weak and inflows were low, there was little to no apparent riverine zone and the lacustrine zone dominated the reservoir [3]. Thus, reservoir retention time (R) was strongly influenced by inflows. Straskraba et al. [114] discussed the likely role of R on the extent of the three reservoir zones. They speculated that under short retention times ($R < 10$ days) the whole reservoir may be considered to be within the riverine zone. Conversely, when there is little advective inflow, and retention times are very long (R > 200 days), virtually all of the reservoir will be within the lacustrine zone [114].

Zooplankton communities are often found to exhibit spatial trends that are related to reservoir zonation and responses to inflows. Marzolf [140] pointed out that zooplankton quickly respond to resource gradients. In addition, reservoir gradients resulted in a pattern of zooplankton distribution with elevated population densities in the transition zone of a reservoir, though the location of this zone clearly was dependent on inflows [140]. Havel and Pattinson [54] reported pronounced spatial structure of zooplankton with the highest densities occurring in the transition zone; this observation is consistent with patterns seen in Kansas [140] and Texas [43]. Soballe and Threlkeld [112] found that short residence times nullified the stimulation of inflowing nutrients on algal biomass in smaller reservoirs of Oklahoma. Dirnberger and Threlkeld [21] and Threlkeld [126] further showed that flushing markedly influenced the structure of reservoir zooplankton communities.

Phytoplankton communities are also strongly influenced by inflow events, primarily through hydraulic flushing and increased nutrient pulses [100]. As reviewed above, phytoplankton production is driven by hydrology, nutrient availability, light limitation, and other physical factors in the various zones of reservoir systems [65, 137] (Table 26.1). Previous authors have also examined how climate change may increase the likelihood, expansion and severity of harmful algal blooms [7, 90, 91, 98, 99]. For reservoirs, freshwater inflows are increasingly reported to influence harmful algal blooms. Vilhena et al. [136] predicted development of an observed major cyanobacterial bloom when an Australian reservoir with drought-induced low pool levels received a large inflow event. Specifically, river inflows high in nutrients apparently stimulated development of a bloom dominated by *Microcystis* sp [136]. Conversely, several studies identified how inflows may terminate harmful blooms of cyanobacteria and other harmful algae. Mitrovic et al. [144] demonstrated how increased flows terminated a cyanobacterial bloom located upstream of a low-water dam on the Lower Darling River, Australia. Similarly, Brooks et al. [9] identified that increased inflows ameliorated a harmful bloom of the haptophyte *Prymnesium parvum* in Dunkard Creek, Pennsylvania. This bloom decimated fish and shellfish in the river, which is impounded by several low-water dams [9].

Such observations are consistent with those of Roelke et al. [98], who documented how inflows to Lake Granbury, an impoundment of the Brazos River in central Texas abruptly terminated a large-scale fish kill resulting from bloom formation of *P. parvum*. Prior to those inflows, severe drought conditions had promoted increased salinity and development of a severe *P. parvum* bloom [98]. With 30% hydraulic dilution, the harmful bloom was terminated, ambient toxicity was ameliorated, and zooplankton densities quickly increased by over 200-fold [106]. Roelke et al. [99] further demonstrated the decade-long impacts of decreased inflows and drought-induced salinization on harmful blooms of *P. parvum* among a chain of three impoundments, which included Lake Granbury. Thus, Roelke et al. [99] and Mitrovic et al. [144] suggested that managing instream flows represents a potentially useful approach to minimize harmful blooms. Under drought conditions, Grover et al. [50] predicted that harmful blooms may initiate in coves that are hydraulically isolated from the main channel of a reservoir. Thus, such coves, which may not receive inflows under non-storm conditions, represent useful management units for preemptive mitigation of harmful bloom formation using various manipulations [50]. As explored further in our case study presented below, decreased inflows commonly occur in southwestern and south-central U.S. reservoirs during or following drought conditions, which are predicted to increase with climate change [98, 99].

In semi-arid and arid regions, inflows to reservoirs may receive, be dominated by, or even be dependent on return flow effluents from wastewater treatment plants. This trend is likely to increase, as the number of permitted discharges increases in response to urbanization [10]. Effluent-dominated streams present unique challenges to water resource managers and introduce a variety of chemical stressors to surface waters [10, 52, 57]. In addition to containing complex mixtures of various anthropogenic contaminants (e.g., metals, pesticides, pharmaceuticals, other industrial chemicals), effluent-dominated streams are also known to often have elevated nutrient levels [134]. The quality of discharged effluent varies temporally although the volume of annual effluent loadings to reservoirs remains relatively stable [10]. What is less understood is how loadings of nutrients and other contaminants from effluent-dominated streams influence limnological processes and water quality management in reservoirs, particularly under low-flow conditions. However, with climate change predictions of increased drought [16], the influence of effluent-dominated streams on base flows of rivers and streams deserves additional study [10]. This is particularly true for streams that were formerly intermittent tributaries, and during droughts because waste load allocations and ambient water quality monitoring efforts (e.g., for chemical constituents, ambient toxicity, and bioassessment) are generally performed during low-flow periods (e.g., defined by 7Q2 or 7Q10) [129]. How climate change may introduce uncertainty in environmental assessments that rely on currently defined low-flow conditions for regulatory compliance also deserves attention in the future [133].

26.4 Reservoir P:R, Diel Ph and Dissolved Oxygen, and Site-Specific Contaminant Hazards

As noted above, climatological conditions may affect ecosystem processes that influence the transportation and redistribution of nutrients in lakes and reservoirs and therefore determine the nature and intensity of biological and biogeochemical processes [15]. For example, the ionic composition of surface waters may be affected by seasonal or annual variability in precipitation that influence hydrology and transportation of allochthonous nutrients from surrounding watersheds [14, 36, 96, 113]. Climate also affects successional shifts of phytoplankton and macrophyte communities that could influence the carbon dioxide demand of aquatic systems. Maberly [73] described scenarios in which inorganic carbon in surface waters may become uncoupled from concentrations of carbon dioxide in the atmosphere due to high rates of biological transformation related to primary production.

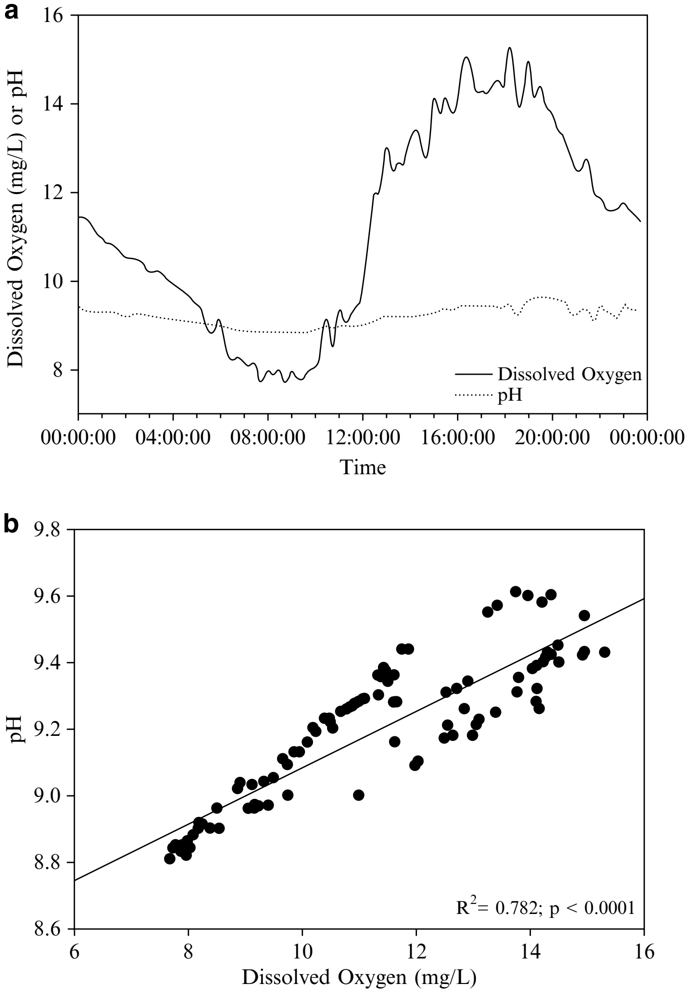


Fig. 26.1 Diel (24-h) dissolved oxygen and pH data (**a**) and the relationship between diel dissolved oxygen and pH data (**b**) for a riverine station in Lake Conroe, Texas, during July 2005

Several researchers have noted substantial diel oscillation in pH at both riverine [12, 44, 51, 85, 123] and lacustrine sites [15, 58, 73, 119]. These diel pH patterns are attributed to assimilation of inorganic carbon for photosynthesis during light hours, followed by continued community respiration at night. Several studies have noted that eutrophication of surface waters can potentiate extreme diel pH oscillations due to high rates of primary production and greater ecosystem biomass [51, 73, 76, 79, 82,145]. Similarly, eutrophication may also spur higher rates of respiration that may eventually lead to increased oxygen demand due to cessation and decomposition of species. Figure 26.1 illustrates this perspective by depicting 24-h data for a representative riverine site in Lake Conroe, Texas, during July 2005, where diel pH values respond directly to dissolved oxygen dynamics.

The interplay of community primary production and respiration and their effects on oxygen dynamics in surface water have been long recognized [88], and the importance of diel patterns of dissolved oxygen are emphasized by protocols for current water quality monitoring efforts [121]. Monitoring efforts for dissolved oxygen recommend that 24-h data profiles are collected, or at minimum, measurements are recorded at multiple intervals throughout the day with at least one targeting the early morning hours [121]. The additional effort for these monitoring approaches is to ensure collection of data representing worst-case scenarios of anoxia. For example, surface water impacted by eutrophication may have elevated levels of dissolved oxygen during the day due to high rates of primary production; however, biological oxygen demand due to community respiration or decomposition may deplete the available oxygen throughout the night when photosynthesis is no longer occurring. These same processes can influence surface water pH and therefore daily discrete measurements may not provide sufficient resolutions for the accurate definition of site-specific pH conditions (Fig. 26.1). Consequently, the failure to monitor and account for diel pH oscillations may introduce uncertainty in environmental risk assessment and management [131, 133].

The potential for contaminants to cause toxicity in aquatic ecosystems is often influenced by site-specific factors [33, 86, 116, 135]. Surface water pH is particularly important because it can change the physicochemical properties of compounds or affect how they interact with other constituents in the water column. Consequently, predictions of environmental fate, bioavailability, and potency for some contaminants can vary appreciably over environmentally relevant surface water pH gradients. Scientists are cognizant of the biological relevance that such variability in pH has on ecological risk assessment and substantial effort has been made to accommodate for site-specific distinctions to reduce uncertainty. Examples of these efforts include the integration of site-specific pH adjustment factors for the derivation of National Ambient Water Quality Criteria (NAWQC) for contaminants such as ammonia [130] and pentachlorophenol (PCP) [128]. The importance of site-specific factors (including pH) for regulatory efforts is also emphasized by the development of biotic ligand models (BLMs) to predict metal speciation and acute toxicity [86].

The completion of bioassays in the laboratory under controlled conditions has allowed researchers to identify pH-dependent toxicity relationships for various traditional contaminants such as ammonia [132], heavy metals [29, 72, 81, 93, 105], contaminants of emerging concern such as pharmaceuticals [28, 63, 84, 131], and harmful algal toxins [46, 134]. However, the effective utilization and application of pH-dependent toxicity data for regulatory efforts is contingent on appropriate characterization of site-specific conditions.

Defining site-specific conditions is challenging for surface water pH because it culminates from various interactions among the atmosphere, hydrology, climate, geomineralogy, and physical morphology that fluctuate both in time and space on various scales [2, 38, 55, 97, 103]. Consequently, understanding site-specific pH and putting it in the context of contaminant hazards for surface waters in general and reservoirs in particular is thus challenged by the spatiotemporal variability observed within and between watersheds [25, 38, 55, 97]. As noted above, within a specific impoundment, site-specific conditions vary both spatially and temporally in different reservoir zones. Whereas differences in surface water pH are partially explained by environmental heterogeneity (e.g., distinctions in geominerology, physical morphology, hydrology, and land use between watersheds), less understood is how the temporal factors causing pH variability introduce uncertainty in environmental risk assessments. Below we present a case studying examining the influence of inflows on diel pH swings in reservoirs and subsequent implications for how sites that are driven by P:R dynamics may influence hazards of select aquatic contaminants.

26.5 Climate Influences on Reservoir Dissolved Oxygen and Ph: A Case Study

26.5.1 Study Locations and Approach

For this case study we selected four impoundments in Texas: Cedar Creek Reservoir, Lake Lewisville, Lake Conroe and Aquilla Lake (Fig. 26.2). Cedar Creek Reservoir is eutrophic, located in the Trinity River Basin, and has a surface area of 138.8 km^2 and a watershed area of 2,589 km^2. Lake Lewisville is also located in the Trinity

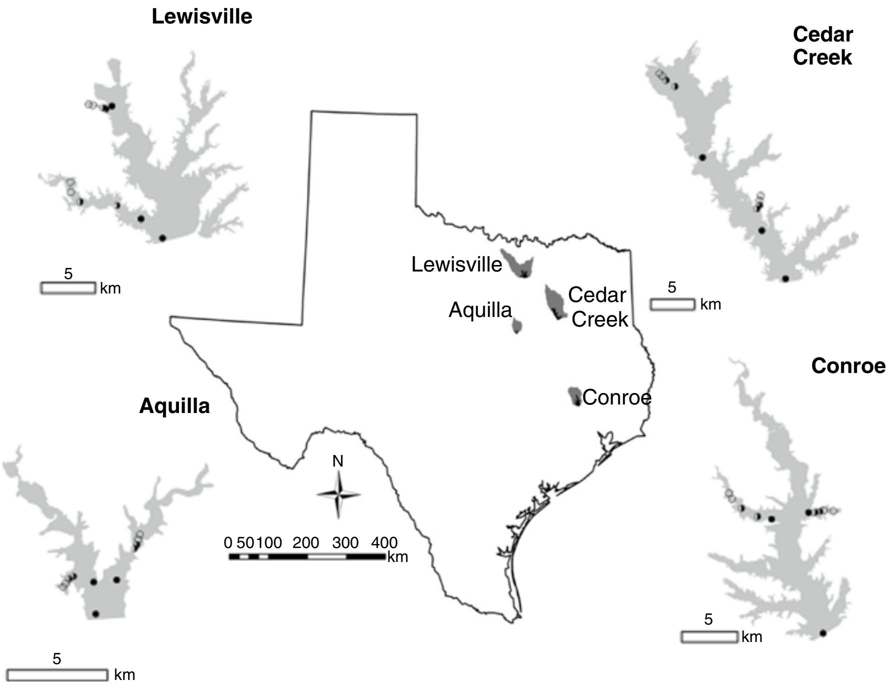


Fig. 26.2 Locations of four study reservoirs and sampling stations (●) in Texas

River Basin and is eutrophic. Lake Lewisville's watershed is highly urbanized, and has a surface area of 94.2 km^2 and a watershed area of 4,299 km^2. Lake Conroe is also a eutrophic reservoir located in the San Jacinto River Basin, and has a surface area of 84.9 km^2 and a watershed area of 1,153 km^2. Aquilla Lake is mesotrophic and located in the Brazos River Basin. Aquilla Lake has a surface area of 13.3 km^2 and a watershed area of 660 km^2.

Land use characteristics associated with drainage basins of each study reservoir are provided elsewhere [40]. The designated uses under the U.S. Clean Water Act for each study reservoir include contact recreation, high aquatic life use, and public water supply. As expected for any reservoir, pool elevations are known to fluctuate based largely on climatic factors and water use patterns. For example, during the 5-year period of 1999–2003, pool elevations in these reservoirs fluctuated from 6 to 20 ft with 74% and 24% of the total pool observations from the reservoirs reported below and above the conservation pool elevation, respectively.

We selected monitoring stations along two riverine to lacustrine gradients in each reservoir to identify the extent of longitudinal changes or gradients of water quality. In addition, a main lake station was chosen for each study reservoir to provide water quality information from the lacustrine zone. Continuous measurements of temperature, pH, dissolved oxygen, and conductivity were continuously monitored at surface depth (~0.3 m) using a YSI 600 XLM® multiparameter datasonde configured with a YSI 650 MDS® multiparameter display system [121]. All water quality data used for statistical analyses passed pre- and post-calibration checks [121]. Methodology used to calculate community P:R followed common approaches [62]. Station locations within either riverine, transition or lacustine zones were further identified using field collected parameters and hydrodynamic modeling [11]. More information on various methodologies, which were employed under a U.S. Environmental Protection Agency-approved Quality Assurance Project Plan, is provided elsewhere [11, 40, 41, 108].

Reservoirs were sampled during summer conditions of 2005 and 2006. During this period, temperatures were warmer than normal and precipitation was lower than normal for most of Texas, though coastal areas received an excess of rain. For example, between April and August 2006 in the Dallas/Ft. Worth region of north-central Texas, mean temperature was 4.5°F warmer and total rainfall was ~60% lower than normal. Such precipitation decreases resulted in lower inflows to reservoirs and decreased reservoir volumes, which is depicted as mean daily pool levels of four reservoirs during 2005 and 2006 (Fig. 26.3).

26.5.2 Community P:R and Diel Dissolved Oxygen and Ph Dynamics

As noted above, Forbes et al. [41] previously reported that when both 2005 and 2006 datasets were considered, Lake Conroe, Cedar Creek Reservoir, and Lake Lewisville were net heterotrophic. In the present case study, we identified that community P:R

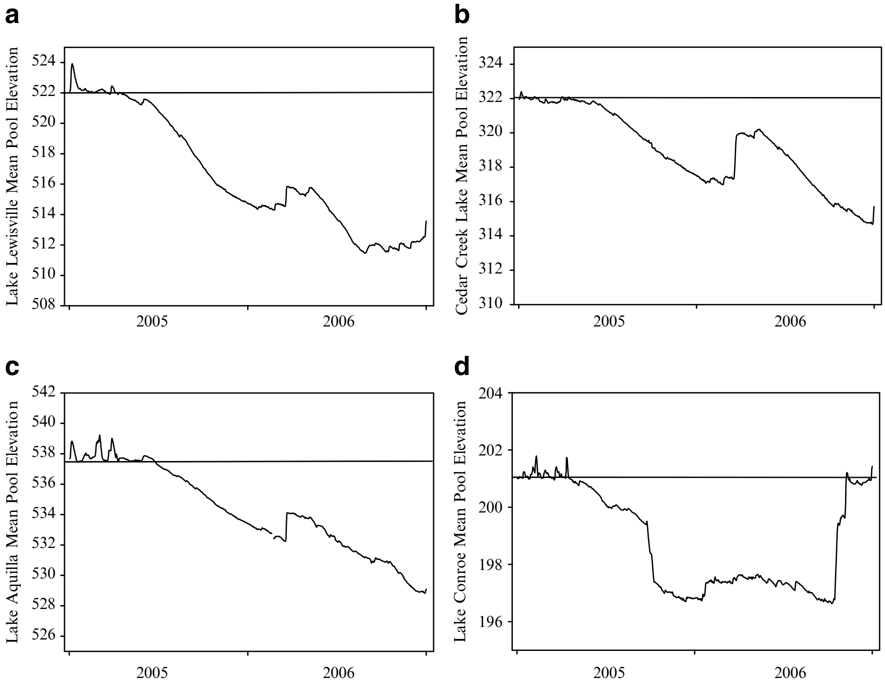
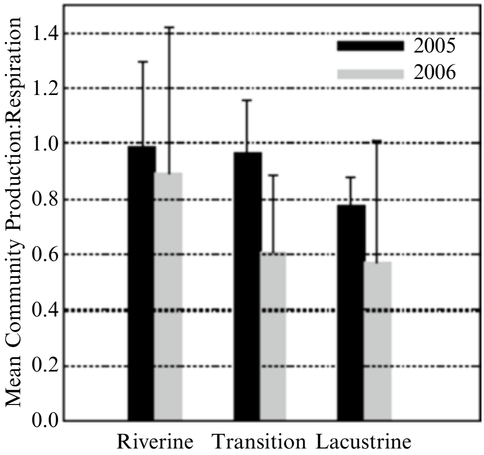


Fig. 26.3 Mean daily pool elevations from 01 Jan 2005 to 31 Dec 2006 for Lake Lewisville (**a**), Cedar Creek reservoir (**b**), Aquilla Lake (**c**), and Lake Conroe (**d**), Texas. *Solid reference lines* identify conservation (normal) pool elevations

(Fig. 26.4) did not conform to historic expectations of P:R ratios along the riverine to lacustrine gradient (Table 26.1). In fact, lacustrine stations were net heterotrophic (P<R). During the drought conditions of 2006, net heterotrophic conditions were more pronounced with both transition and lacustrine zones, which were characterized by P:R less than 1. As noted above, diel dissolved oxygen and pH are coupled (Fig. 26.1). Thus, we examined the magnitude of dissolved oxygen and pH change over 24 h from each sampling station (Fig. 26.5). In 2005, relatively limited dissolved oxygen and pH change was observed in riverine sites, whereas statistically significant relationships were observed between dissolved oxygen and pH change at transition and lacustrine sites (Fig. 26.6). However, such observations were not observed in transition or lacustrine zones during 2006 (Fig. 26.5). Further, pH and dissolved oxygen variability in riverine zones during the drought conditions of 2006 resembled transition zone locations during 2005 (Fig. 26.6). Thus, it appears that reduced inflows during 2006 reduced community primary production relative to heterotropic respiration (Fig. 26.4), which reduced the magnitude of diel dissolved oxygen and pH variability, particularly in the transition and lacustrine zones of these reservoirs (Fig. 26.6). In fact, such observations in these Texas reservoirs are generally consistent with those of Marce et al. [78], who identified decreasing stream flows over a 44-year period to cause an approximate 20% decrease in oxygen levels in Sau Reservoir near Barcelona, Spain.

Fig. 26.4 Mean (±SD) community production : respiration stations located in riverine, transition, and lacustrine zones of Lake Lewisville, Cedar Creek Reservoir, Aquilla Lake, and Lake Conroe, Texas, during summer 2005 and 2006



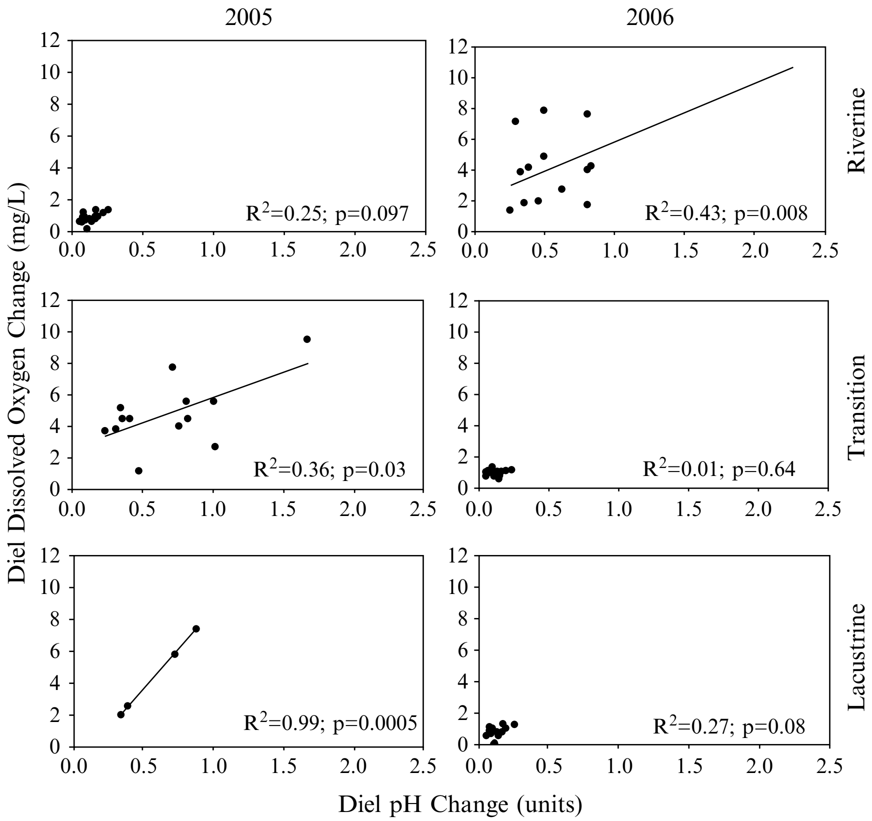


Fig. 26.5 Relationship between diel (24-h) change (maximum–minimum) of dissolved oxygen and pH at riverine, transition, and lacustrine stations in Lake Lewisville, Cedar Creek Reservoir, Aquilla Lake, and Lake Conroe, Texas, during summer 2005 and 2006

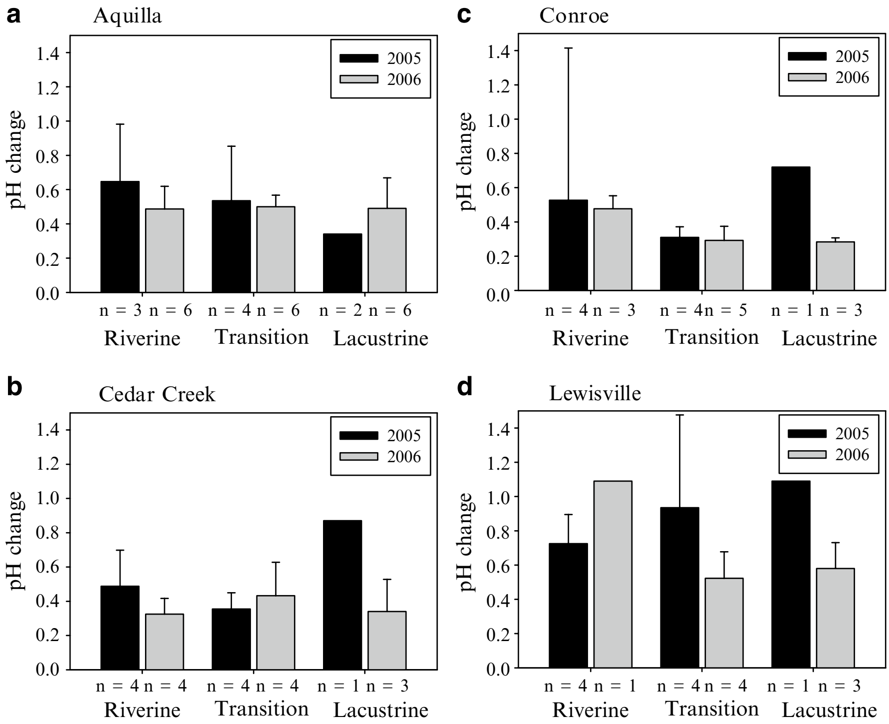


Fig. 26.6 Diel (24-h) pH change (maximum–minimum) at riverine, transition, and lacustrine stations in Aquilla Lake (**a**), Cedar Creek Reservoir (**b**), Lake Conroe (**c**), and Lake Lewisville (**d**), Texas, in summer 2005 and 2006

Below we examine the role of pH on bioavailability and toxicity of metals and ionizable contaminants. We further examine how the pH variability between more traditional (2005) and drought conditions (2006) influenced site-specific predictions of NAWQC values for several model contaminants in riverine, transition and lacustrine zones of the reservoirs examined in this case study. We specifically estimated acute NAWQC concentrations for an ionizable weak acid (PCP), a weak base (ammonia) and copper, using the BLM.

26.5.3 Ph Influences on Metal Speciation, Ionization, and Site-Specific Water Quality Criteria

26.5.3.1 Ph Influences on Metal Speciation and Aquatic Toxicity

Trace element speciation analysis is an approach in which various forms or phases of an element (e.g., simple inorganic species, organic complexes, and absorbed to colloidal particles) are quantified in an environmental sample on an individual basis rather than cumulatively as the total measured concentration [39, 118]. Of course, multiple elemental species may coexist in an environmental matrix simultaneously and their prevalence is determined by various environmental factors. Therefore, defining site-specific conditions is often imperative for grasping either biological or geochemical cycling of elements in the environment [39]. While various factors influence elemental speciation in surface waters (e.g., cations and anions, dissolved organic carbon), pH is often critical because it controls the magnitude and intensity of interactions with other variables.

Elemental speciation is important for environmental risk assessment because the various physiochemical forms of elements generally have unique potencies to aquatic life [39]. Furthermore, differences in site-specific conditions may also dramatically affect environmental fate, transport, partitioning behavior, bioavailability, bioconcentration, and ultimately toxicity [23, 95]. The total elemental concentration in an environmental sample seldom provides sufficient information to accurately infer hazard [31]. For example, many fish and other aquatic species can effectively cope with high concentrations of heavy metals in the food chain or sediments due to their natural defenses against ingested heavy metals, which can be eliminated from the gut and detoxified by metallothioneins [67]. However, it appears that relatively seldom have aquatic species evolved mechanisms to defend them against elemental species that may be rapidly absorbed across the water-gill interface (e.g., free metal ions or toxic lipid-soluble complexes). Therefore, the site-specific risk that a contaminant poses to aquatic organisms is often more accurately predicted by the proportion of that contaminant in a free form [31].

The BLM was developed for heavy metals to support determinations of how site-specific conditions affect metal speciation, an understanding of ambient aquatic toxicity, and risk characterization and management [23]. To illustrate the influence of pH on copper speciation, predictions of the prevalence of free ionic copper (Cu^{2+}) in synthetic waters with varying hardness are illustrated in Fig. 26.7 at 25° C and for a total concentration of 25 µg Cu/L. This observation is critical because ionic copper concentrations are most highly correlated with acute toxicity to aquatic life [23, 95]. In Fig. 26.7, the effects of pH are clear regardless of hardness concentrations. The greatest magnitude of differences in free Cu^{2+} concentration is expected in soft water with a predicted 2000-fold difference between pH 6 and 9.5, whereas the predicted differences for moderately hard and hard water were 1400- and 780-fold, respectively (Fig. 26.7). In the present case study with various reservoir sites, we modeled acute copper NAWQC values using default BLM assumptions, hard water conditions, and maintained temperature at 25°C (the highest possible temperature allowed by the model).

26.5.3.2 Ph Influences on Ionization State and Aquatic Toxicity

Scientists have long recognized that the biological activity of some xenobiotics is markedly influenced by their ionization state [6, 107, 110, 111]. The physiochemical properties of ionizable compounds may vary in the environment depending on

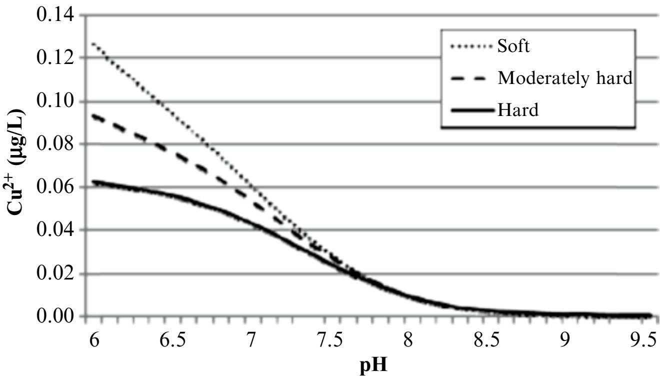


Fig. 26.7 An example of site-specific pH effects on metal speciation, where Cu^{2+} levels were predicted by the BLM, assuming total copper equal to 25 μg Cu/L with either soft, moderately hard, or hard water conditions at 25°C

their dissociation, which is controlled by structural components intrinsic to the compound and the pH of the medium in which it resides. Researchers will often estimate acid dissociation constant (pK_a) for compounds based on their structural attributes, and this value can be related to pH to infer the degree of ionization (or dissociation). Weak acids are generally ionized in solutions when pH > pK_a, whereas weak bases are more ionized when pK_a > pH. The unionized forms of either weak acids or bases are often considered more bioavailable because they have greater propensity to cross cellular membranes due to their lower polarity and greater lipophilicity.

Various chemicals that may be transported or discharged into aquatic systems, such as pesticides, various metabolites, pharmaceuticals, and personal care products, may be ionizable. In fact, some contaminants are specifically designed to be ionizable to maximize their efficacy for intended use. For example, approximately 75% of the essential medicinal drugs described by the World Health Organization and approximately one-third of modern pesticides have ionizable groups [77]. In the case of pharmaceuticals, many are often administered orally and therefore must first pass through the digestive tract and then be transported via the blood to the target area. Because various regions of the body have different pH (stomach: pH 4; blood: pH 7; CNS: pH 8), the bioavailability of drugs will often change within the body [32]. Thus, the influences of pH on bioavailability, efficacy, and toxicity are critical considerations for weak acids and bases found in various environmental or biological matrices.

The importance of ionization state to environmental risk assessment is emphasized by the integration of site-specific pH adjustment factors in NAWQC for compounds such as ammonia (NH_4) [132] and PCP [128]. As expected, both the weak base NH_4 (pK_a = 9.3) and the weak acid PCP (pK_a = 4.7) are more toxic to aquatic life when they occur in the environment predominately as the unionized forms. To account for pH-dependent effects on potency, pH adjustment factors are derived by relating site-specific pH to laboratory-derived toxicological data from experiments completed with the compound of interest at various ambient pH levels (e.g., ranging from pH 6 to 9). Site-specific pH consideration can result in markedly different acceptable loads in receiving systems; varying by 13-fold for NH_4 and 60-fold for PCP between sites with contrasting pH values of 6 and 9.

However, analysis of effects during environmental risk assessment is often traditionally completed by collecting data for laboratory toxicity tests in which individuals of a single species are exposed to a known concentration of contaminants [63, 131]. These exposures are typically completed under specific conditions that are stable to allow for repeatability; however, this approach may not accurately capture the potential for all contaminants to cause biological effect. For a select number of ionizable organic contaminants in which their physicochemical properties are known to change appreciably depending on the pH of the solution where they reside, including ammonia, PCP, and more recently for some pharmaceuticals [63, 84, 131] and antimicrobials [89], experiments have quantified the magnitude of difference in biological responses over environmentally relevant pH gradients. Kim et al. [63] recently noted greater toxicity at lower pH for several acidic pharmaceuticals, which was attributed to the ionization of the compounds and ultimately their bioavailability being pH-driven.

26.5.3.3 Site-Specific Ph Influences on Reservoir Water Quality Criteria

In the present case study, variation in surface water pH profiles led to statistically significant differences ($p < 0.05$) in acceptable criterion maximum concentration (CMC) NAWQC for copper, ammonia and the weak acid pesticide PCP among the reservoir zones between study years (Fig. 26.8; Table 26.2). Using the BLM, the predicted NAWQC for copper was substantially higher in Cedar Creek Reservoir and Lake Conroe due to the higher ambient pH observed at these reservoirs compared to Aquilla Lake and Lake Lewisville (Fig. 26.8). Interestingly, predicted NAWQC varied substantially at similar sites within the same reservoir between 2005 and 2006. For example, there was nearly a 10-fold difference in the NAWQC for copper between the lacustrine zone stations of Cedar Creek as mean concentrations for 2005 and 2006 were modeled to be 238 and 31 μg/L, respectively. Temporal effects were less pronounced in some of the other studied reservoirs as mean copper CMC NAWQC were nearly identical between 2005 and 2006 for transition and lacustrine zones and only varied by 28% in the riverine zone of Aquilla Lake.

In addition to variability between reservoirs, notable differences in NAWQC for copper were also observed among the riverine, transition, and lacustrine zones within the same reservoir, especially during drought conditions (Fig. 26.8). For example, the magnitude of effect related to longitudinal gradation was evident for copper in Cedar Creek during drought (2006) as mean NAWQC CMC for riverine and transition zones were 7–10 times higher compared to the lacustrine zone. Alternatively, NAWQC for copper in Lewisville Reservoir showed an opposite pattern as the lacustrine zone had values 1.7 times greater than the riverine zone during 2005.

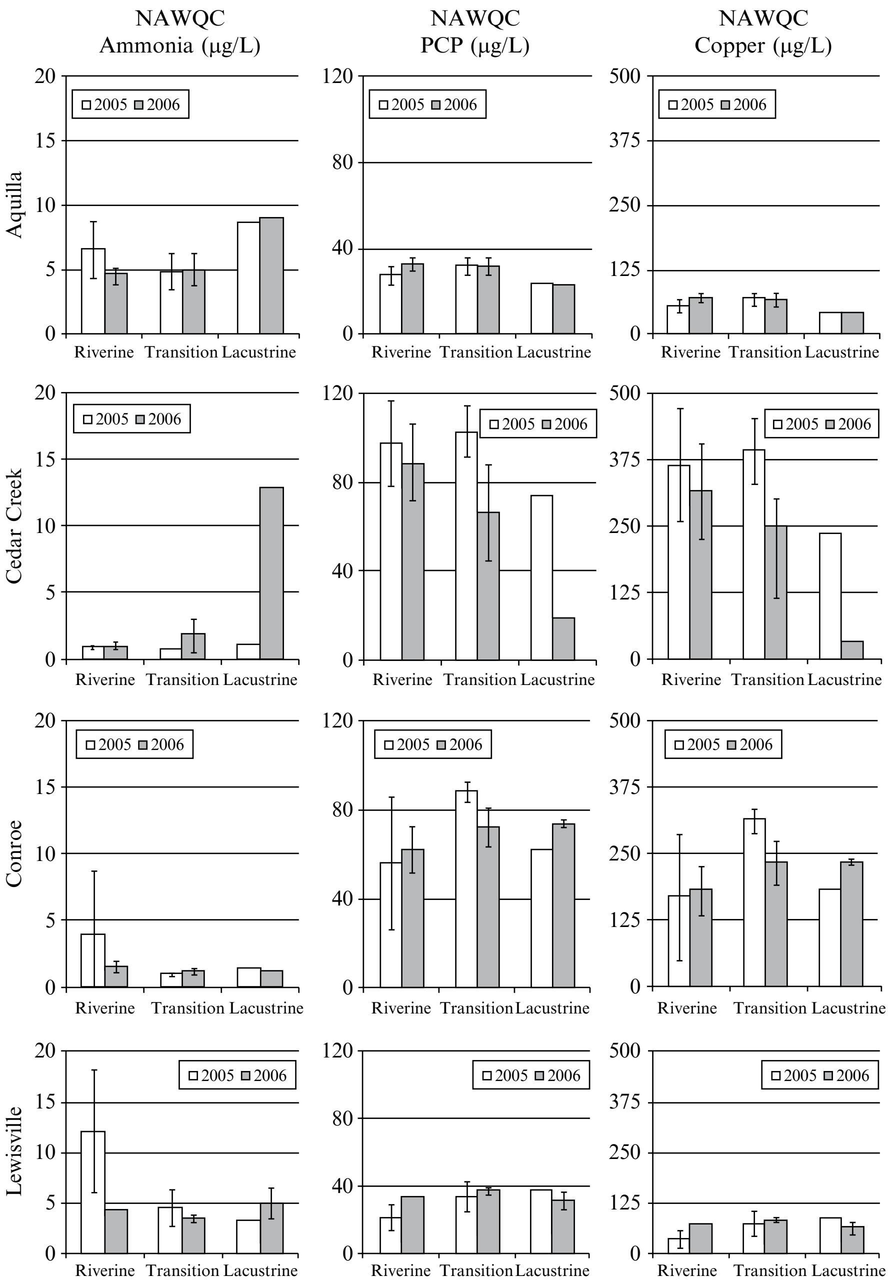


Fig. 26.8 Mean (±SD) predicted NAWQC CMC values of ammonia, PCP, and copper at riverine, transition, and lacustrine stations in Aquilla Lake, Cedar Creek Reservoir, Lake Conroe, and Lake Lewisville, Texas, in summer 2005 and 2006

Table 26.2 Influence of reservoir zone (riverine, transition, lacustrine) and year (2005, 2006) on predicted CMC NAWQC values for ammonia, PCP, and copper

Reservoir	Variable	Ammonia	Pentachlorophenol	Copper
Aquilla	Zone	*	*	*
	Year			
	Zone × Year			
Cedar Creek	Zone	***	***	**
	Year	**	**	**
	Zone × Year	***	*	
Conroe	Zone			
	Year			
	Zone × Year			
Lewisville	Zone	*	"	"
	Year			
	Zone × Year			

Empty, $p>0.1$; ", $p<0.1$; *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$

The predicted NAWQC CMC for ammonia and PCP varied appreciably among the study reservoirs (Fig. 26.8). For ammonia, a weak ionizable base, NAWQC were markedly lower in Conroe and Cedar Creek due to higher surface water pH. The opposite was observed for the weak acid PCP and both Aquilla and Lewisville had appreciably lower acceptable water column concentrations than the other reservoirs (Fig. 26.8). The effects of flow on the potential hazard of these ionizable contaminants were emphasized by substantial differences in predicted NAWQC between 2005 and 2006. For example, mean ammonia NAQWC values for transition and lacustrine zones of Cedar Creek were 11 and 2 times higher in 2006 than in 2005 (Fig. 26.8). The effect of year was also apparent in the mean NAQWC for PCP in Cedar Creek and again the magnitude of effect was most pronounced at the lacustrine sites as the respective means varied by 4- and 8-fold between the 2 years (Fig. 26.8). However, unlike for ammonia, the NAWQC for PCP in Cedar Creek was markedly lower in 2006 compared to 2005.

There were also clear distinctions among mean NAWQC values for ionizable contaminants over longitudinal gradients in several of the reservoirs and magnitude of these effects appeared related to hydrology. For example, in 2006 the mean ammonia NAWQC was approximately 14 and 7 times lower the riverine and transition zones, respectively, compared to the lacustrine zone of Cedar Creek (Fig. 26.8). Longitudinal effects were also apparent for Conroe and Lewisville in 2005 as allowable ammonia concentrations were 3–4 times higher and far more variable in riverine zones compared to the transition or lacustrine zones.

26.5.4 Implications for Site-Specific Reservoir Water Quality Assessment and Management

Several researchers have demonstrated how diel cycles in pH and dissolved oxygen at riverine sites may affect surface water concentrations of trace metals if they are released from sediments. For example, Nimick et al. [85] recorded minimum metal concentrations for several metals in the mid-afternoon, but these levels increased by 100–500% during the evening and peaked just before sunrise. Gammons et al. [45] noted that dissolved concentrations of Fe(II) and Cu in streams decreased during the day by 10- and 2.4-fold, respectively. The substantial variability in observed metal concentrations over the course of the day emphasizes that biogeochemical processes affecting their environmental behavior are dynamic. Perhaps more importantly, short-term variability in metal concentrations and speciation associated with hourly or daily time scales can in fact be of similar or greater magnitude than those previously attributed to seasonal or yearly variability [83, 123]. For example, Nagorski et al. [83] describe scenarios in which short-term (daily, bi-hourly) variation of several geochemical parameters actually accounted for a majority of the variability once thought to represent fluctuations due to much coarser seasonal time scales. In other words, the timing of collection of discrete samples over the course of the day may introduce more uncertainty to the analysis of exposure phase of environmental risk assessment than collecting samples at much broader seasonal or yearly intervals.

Studies have also shown that changes in ionization state due to differences in site-specific pH can affect bioconcentration factors (BCFs) for some organic compounds Endo and Onozawa [28], Fisher et al. [37], and others have demonstrated that increased BCFs correspond to heightened toxicological responses [34, 66, 84]. When the site-specific differences in pH observed in reservoirs presented in the present case study are considered, it appears highly probable that the environmental risk of some ionizable contaminants that may be found in these reservoirs vary depending on P:R dynamics. For a gradient of wadeable streams in central Texas, Valenti et al. [133] demonstrated the importance of climate change on instream flows, diel pH variability, and aquatic hazards during the drought conditions of 2006 and extremely wet conditions of 2007. Specifically, Valenti et al. [133] described scenarios in which NAWQC for ammonia varied 20-fold at a site over the course of the day due to diel pH variability. Furthermore, the magnitude of difference among site-specific potencies for ammonia and the weak base pharmaceutical sertraline were actually considerably greater than the relative difference in mean NAWQC or predicted toxicological responses between years (2006, 2007) with strikingly different instream flows [133].

Other studies have demonstrated that patterns of diel pH oscillation have potential water quality implications because internal contaminant exposure scenarios for individuals may vary over the course of the day. In a study not focused on steady state concentrations, Hargreaves and Kucuk [53] demonstrated rather that total ammonia-nitrogen concentrations in the plasma of juvenile hybrid striped bass, channel catfish, and blue tilapia varied as a result of environmentally relevant daily oscillations in exposure pH. Similar trends in changing internal doses could occur for other ionizable contaminants, but less understood is how the magnitude, frequency, and duration of sporadic fluctuations in concentrations at specific target sites within the body will affect pharmacological or toxicological responses in aquatic organisms. Thus, how long and how often must site-specific pH be above or below a specific threshold before it affects estimates of environmental hazard for ionizable contaminants?

This question could be answered by examining site-specific pH in relation to pH-dependent toxicological relationships integrated over the course of a day. For example, a probabilistic analysis could support determining the duration and magnitude of contaminant hazard exceeding an acceptable threshold of toxicity for specific proportions of the day. Thus, instead of determining toxicological thresholds (e.g., LC50) as a function of pH, it would also be useful to define time to adverse responses (e.g., LT50) with diel pH variability. Such an approach deserves additional consideration.

The question could also be addressed by developing aquatic toxicokinetic models that take into account rates of uptake and deprivation under stochastic environmental conditions. These models allow for extension beyond the traditional approaches of simply measuring contaminant concentrations in a water sample and thus further support considerations of how site-specific conditions may affect internal body concentrations or doses of xenobiotics [19]. Recently, it has become apparent that uptake of ionizable organic contaminants cannot solely be explained by the availability of the unionized moiety [30]. While this may be partially attributed to uptake by means other than passive transport at the gill (e.g., by transporters) or other dermal surfaces, it may also be caused by an organism's ability to maintain xenobiotics once they are absorbed. Wheeler and Hellebust [143] described how differences in the internal pH of some organelles in plant cells may serve as reservoirs for alkylamines. For examples, pumping H^+ into vacuoles could reduce pH and allow some cells to accumulate amines at concentrations 10^3- to 10^4-fold higher than external media. Similar mechanisms may be at play for aquatic organisms based on the pharmacokinetic principle that body compartments may vary in their specific pH. Therefore, by melding toxicokinetic with pharmacokinetic principles and relating modes-of-action to specific target locations within the body, aquatic scientists could more appropriately determine the relative and site-specific risks of different ionizable contaminants, including contaminants of emerging concern [19].

26.6 Conclusions and Recommendations

Here we reviewed the various physical, biological, and chemical dynamics of reservoir zones, which distinguish them as uniquely different aquatic habitats, and we examined the role of inflows on reservoir water quality. Further, using a case study of four reservoirs in Texas, we demonstrated that daily variability has direct implications for how we should collect, analyze, and interpret site-specific water quality data, particularly among reservoir zones when inflows are influenced by climatic variability. Based on our experiences, we provide the following recommendations for reservoir water quality assessment and management, particularly given the prospects of increased frequency and duration of drought conditions in the southwestern and south-central U.S [16, 74].

Regulatory, management, and assessment efforts should account for the reservoir-specific characteristics that constitute the major drivers for water quality. These include reservoir morphology, hydraulic retention times, watershed land uses, timing, quantities and sources of inflows, and resident biological communities that constitute threats (e.g., harmful algal blooms) or represent sensitive resources (e.g., threatened and endangered species). Protecting such resources essentially involves managing worst-case scenarios that, for example, could occur in summer months during periods of drought. Thus, the timing and location of assessment sampling should be chosen so as to best evaluate the greatest threats to the site-specific resources.

We specifically recommend the integration of an alternative approach for defining site-specific pH at riverine, transition, and lacustrine sites using 24-h continuous monitoring data. This approach would allow researchers to determine the probability of encountering a specific pH at a site. Alternatively, we recommend that samples should be taken both in the early morning before sunrise and in the late afternoon near sunset, when net community respiration and net community production, respectively, are expected to be greatest (Fig. 26.1), to identify diel pH variability at sampling sites. At a minimum, diel pH variability should be considered in the design of study plan and long-term monitoring efforts. Current approaches for defining site-specific pH for NAWQC often include using the 15th centile of a minimum of 30 discrete samples [121]; however, as demonstrated here and elsewhere [131, 133], this approach may introduce substantial uncertainty in environmental risk assessment due to diel variability of pH.

Previously, there has been substantial effort towards defining pH-dependent toxicological relationships for traditional contaminants such as ammonia, PCP, and heavy metals. However, we advise that similar strides must be taken to better understand the potential hazard of contaminants of emerging concern, such as parent compounds, metabolites, and degradates of pharmaceuticals and other industrial chemicals. Often, the effects of pH on the physicochemical properties of pharmaceuticals are extensively studied such that pharmacokinetics and environmental fates can be predicted; however, a similar emphasis should also be made to identify how pH may affect their potency to aquatic life [131].

As demonstrated in this study, water quality parameters may shift appreciably over the longitudinal gradients of various reservoir habitats in response to inflows. This presents an environmental management challenge as changes in site-specific conditions can alter the aquatic hazard of some contaminants. Monitoring reservoir water quality only at dam (e.g., lacustrine) sites, for example, fails to provide representative information for the assessment and management of water quality in riverine and transition zones of reservoirs, particularly when inflow patterns are modified by climatic changes.

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Chapter 27
Climate Risks

Some Efforts in Russia and Request for High Temporal Resolution Climate Series

A. Sterin

Abstract The paper contains two main parts. The first part is an overview of recent climate-related official documents that were prepared and published in the Russian Federation. The second part contains description and interpretation of some approaches to assess climate variability and climate trends in time series of climate characteristics, which are vital to assessing climate risks. Unlike some traditional approaches to climate trends and related climate risk estimations, an approach that provides more detailed description of climate trends—but needs more detailed description of climate processes on a temporal scale—is recommended and interpreted. Some graphs of climate trends are provided. Plots of climate trends as a function of quantile values of temperatures are provided.

27.1 Introduction

Several very important documents related to climate and climate change were prepared and published in the Russian Federation recently. Some of them are high-level (presidential or governmental); others are detailed assessment documents. These documents, their level and content, as well as their spirit, are obvious demonstrations of high attention that is given to climate problems in Russia. We provide information on three main recent documents relating to climate issues in the Russian Federation. They are:

1. Climate Doctrine of the Russian Federation [2]
2. Strategy of Activities in the Field of Hydrometeorology and in the Adjacent Fields for the Period up to 2030 (Considering Aspects of Climate Change) [8]

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3. Assessment Report on Climate Change and Its Consequences in the Russian Federation [1]

Also, we discuss the motivations, goals, and ideas of these documents, mainly in the form of citations. References to corresponding web resources containing electronic copies of the documents are provided.

In the second part of the paper, we will provide descriptions of approaches to assess tendencies in climate change. High temporal resolution of observed data will be needed for that, and it will become possible to obtain more informative outputs, that should be interpreted. Mr. Arsenii Timofeev (RIHMI-WDC) provided a lot of materials that are partly assessed in this part of paper. His contribution is highly appreciated.

27.2 Recent Climate-Related Documents in the Russian Federation

27.2.1 Climate Doctrine of the Russian Federation

In December 2009 President D. Medvedev adopted the document, “Climate Doctrine of the Russian Federation” (the Doctrine). This document was prepared mainly by the Federal Service on Hydrometeorology and Environmental Monitoring (Roshydromet), a leading agency in Russia in climate studies and monitoring. An unofficial English version is available online [2]. The description below includes several citations from this unofficial translation.

The Doctrine is a brief (16 pages), highly concentrated, high-level document. The Doctrine represents an overview of the goals, principles, substance, and methods of implementation of a unified public policy for the Russian Federation, both within its borders and in the international arena, on the issues related to climate change and its consequences [2]:

> Global climate change in the Russian Federation (taking into account its territory, geographical situation, exceptional variety of climatic conditions, economic structure, population problems, and geopolitical interests) creates a situation that suggests a need for the early development of a comprehensive and balanced public approach to climate problems and related issues based on the complex scientific analysis of environmental, economic, and social factors.

The Doctrine contains several parts that describe approaches to various climate-related problems for Russian Federation:

- Goal and principles of climate policy
- Definition of climate policy
- Distinctive features of the Russian Federation that need to be taken into account in addressing the climate change problem
- Implementation of the climate policy
- Executors of climate policy

Climate policy in Russia is oriented to achieving strategic goals:

> Strategic goal of climate policy is to achieve secure and sustainable development of the Russian Federation, including institutional, economic, environmental and social as well as demographic aspects of development in the context of changing climate and emerging challenges.

A significant principle is the following:

> The interests of the Russian Federation concerning climate change are not limited to its territory and have a global nature. This situation can be explained by the global nature of climate change as well as by the need to take into consideration in the area of international relations the diverse impacts on the climate and the consequences of climate change in various parts of the world.

The distinctive features of the Russian Federation are listed in the context of both negative and positive possible consequences of climate change for the Russian Federation. The lists of negative and positive possible consequences are well balanced; there seems to be much reason in considering and in taking into account both of them, rather than to concentrate only on negative factors.

Negative effects of the expected climate change for the Russian Federation, as noted in the Doctrine, include increased health risks among certain social groups; increased recurrence, intensity, and duration of droughts in some regions; and extreme precipitation patterns, floods, and soil overmoisture, dangerous for agriculture; in others, increased fire risk in forest areas, permafrost degradation in the northern regions causing damage to buildings and communications lines, ecological balance upset, including displacement of one species by others, prevalence of infectious and parasitic diseases, and increased electric power consumption for air conditioning in summer in many human settlements.

On the other hand, possible positive effects of the expected climate change for the Russian Federation with a significant potential for efficient sectoral and regional economic development include such essential pluses as decreased energy consumption during heating seasons, an improved ice situation, and, consequently, conditions of freight hauling in the Arctic seas (this will provide an easy access to the Arctic shelves and their exploration), improved structure and expansion of plant cultivation areas, increased efficiency of cattle breeding, and increased productive efficiency of boreal forests.

The Doctrine underlines the specifics of the Russian Federation, unique conditions for considering climate change factors:

> Exceptional … variety and scale of climate change in the regions of the Russian Federation and their consequences for its environment, economy and population are a natural result of its immense territory and the diversity of natural conditions. While formulating climate policy, including the positioning of the Russian Federation within the international community, it is necessary to take into account the combined effect of the low average population density and immense territory leading to higher transportation needs (both directly for the population and for the infrastructure serving the needs of the government, population and economy) and cold climate resulting in additional heating needs, as well as the production and transportation of significant volumes of fuel and energy resources [2].

All these factors are vital for taking into account while addressing climate change specifics for the terrestrial (but not only for the terrestrial!) systems.

A vast list of actions oriented to climate policy implementation is contained in the Doctrine document. These implementations consider all the main areas of climate policy [2]:

- Establishment of legal and regulatory frameworks and government regulations in the area of climate change.
- Development of economic mechanisms related to the implementation of measures to adapt to and mitigate human impact on climate.
- Scientific, information, and personnel support for the development and implementation of measures aimed to adapt to and mitigate human impact on climate.
- International cooperation in the development and implementation of measures to adapt to and mitigate human impact on climate.

The main executors of climate policy are: federal authorities, federal state bodies of the constituent entities of the Russian Federation and the local government bodies, organizations including public organizations (associations), mass media, and households. The Doctrine contains a detailed list of activities of each of the executors. Some factors of relationships between the executors, including possible conflicts of interest, are mentioned and need to be taken into account. The final paragraph of the Doctrine states:

> The implementation of the climate policy involves development on its basis of federal, regional and sectoral programmes and action plans [2].

Several programs and action plans have been instituted in the Russian Federation to implement the Doctrine.

27.2.2 Strategy of Activities in the Field of Hydrometeorology and in the Adjacent Fields for the Period up to 2030 (Considering Aspects of Climate Change)

The second document that is related to climate in the Russian Federation is a high-level document entitled, "Strategy of Activities in the Field of Hydrometeorology and in the Adjacent Fields for the Period up to 2030 (Considering Aspects of Climate Change)" (the Strategy) [8]. The Strategy was adopted at the direction of the Government of the Russian Federation on 03 September 2010. Roshydromet performed a vitally essential role in preparation of this Strategy. An English translation is not yet available. The Strategy is a vast and comprehensive document, reflecting not only climate issues, but a vast list of directions to provide security of the country and measures against disasters of natural and technical origin, and measures to protect the environment and decisions oriented to increase the efficiency of weather-dependent fields of economy (such as water sector, agriculture, transportation, and energy). The Strategy contains a section on developing national research in the field of climate. The problems outlined to be solved include [8]:

- Create and develop climate datasets and databases on all components of the climate system, which will enable to the formulation of scientifically substantial conclusions on climate state and on climate change.

- Create and develop Russian state-of-the-art, world-class climate models, developing and modernization of blocks in these models, which take into account various components of the climate system, as well as support of climate modeling efforts by sufficient computational and telecommunication resources.
- Develop methods of regionalization of climate model outputs and work out recommendations on taking into account factors of changing climate for certain regions of the country, consistent with the level of social and economic development of these regions.
- Develop methods of inventorying sources of emissions and sinks of greenhouse gases.
- Work out the criteria, parameters (threshold values), and conditions of climate safety in the Russian Federation.
- Research possible global and regional climate changes, their consequences, the estimation of economy sectors and regional vulnerability, possible regional adaptation to climate change, and possibilities for mitigation of potential anthropogenic impacts.
- Independently evaluate and review world climate and associated research results.

27.2.3 Assessment Report on Climate Change and Its Consequences in the Russian Federation

The third very important publication is an “Assessment Report on Climate Change and Its Consequences in the Russian Federation” (Assessment Report). This is a multivolume publication published in 2008 and giving very vast and detailed background for future high-level documents, including the abovementioned Doctrine. The Assessment Report includes a General Summary (in Russian and in English), and the following Technical Summary volumes in Russian: Volume I: “Climate Change in Russian Federation” and Volume II: “Consequences of Climate Change in Russian Federation” [1].

There was a strong need to prepare such a comprehensive publication. The influence of IPCC Assessment Reports was necessary but not sufficient for understanding climate specifics and working out climate adaptation and mitigation actions on the national level. There was a strong need to produce an assessment oriented to the national level:

> The IPCC assesses available scientific, technical and socio-economic information on climate change and its impact, as well as on options for mitigating climate change and adapting to it. Outcomes of such studies are published periodically as the IPCC Assessment Reports, and … four reports have been issued (in 1990, 1996, 2001, and 2007). As the Intergovernmental Panel, the IPCC is responsible for the submission of objective scientific findings to the world community for the elaboration of a global and regional development strategy. Furthermore, it is expected that governments can take into account the IPCC findings and subsequently apply them to both the development of internal policy and the adoption of relevant actions resulting from international agreements [3].

As stated in the preface to the General Summary

> …The IPCC reports, which are aimed mainly at global assessments, cannot provide a complete picture of regional climate changes and its impacts. Further development and implementation of practical measures are required to reduce the anthropogenic influence on the climate system and mitigate its consequence at the national level. Therefore, in addition to IPCC activities, many countries carry out assessments at national levels employing comprehensive data sets collected by national hydrometeorological services, thoroughly use results of national research, and take into account inherent regional features and social conditions…[1]

27.3 Assessing Climate Variability and Trends: Some Instrumentation Issues

This paper has listed only a few recent, available climate-related documents. Though specific to the Russian Federation (and taking into account its numerous features), these documents raise numerous problems that are common to all countries, as well as all humankind. IPCC Assessment Reports contain these problems formulated in a very concentrated well-weighted sounding. The particular problems formulated in the first volumes of the previous IPCC reports (i.e., in the volumes dedicated to the physical science basis of climate change), include, among others, "Is the climate becoming warmer?" and "Is the climate becoming more variable and more extreme?" [3]

These questions are interrelated, but, in a certain sense, they call for different scientific approaches. Also, they need researchers with different technical and technological capabilities. While the first question is traditional in climate science, and results have been collected (at least for surface territories and for the atmosphere above terrestrial areas [7]) since the 1960s and even earlier, the second question has attracted vital attention in the past two decades. Moreover, the technical capabilities required to address this question (including a long time series of observations; databases capable of supporting needed data management operations; and adequate hardware and software to process, analyze, and visualize data and results) have become available in just the past few years.

To get a general answer to the first of these questions, it is, at least in most cases, enough to estimate some changes in the average state of climate (e.g., changes over decades of annual mean temperature, or in seasonal mean temperature, taken into account for each year of a long period). The climate trends are then calculated based on series of such figures; each of them is an averaging characteristic.

That is not the case when we try to answer the second question: the mean values (for example, monthly mean temperature values) carry only very general information. Within 1 month there could be positive and negative variations in temperature on certain days, which balance themselves over the month so that the average is unaffected; however the individual extremes could have serious social and economic effects. For example, a sudden night freezing in May in middle and southern Russia, where even a single cold night may be sufficient to damage garden plants, would not noticeably affect monthly average values. Experts in climate analysis and prediction, who understand these effects, are careful in their judgments about monthly estimates and predictions.

To address such an effect, even in our desire to answer even this first (much more simple!) question, and, moreover, to answer the second question, it is better to study what happens with the whole distributions of measured values, because mean value is just one (and not most informative!) of many characteristics of distributions. When we assess the whole distribution of values (say, temperature values within a certain month, presented graphically in the form of histogram or in other graphical informative formats, or in numerical form), we can analyze its form in detail, whether it is symmetric or skewed, what are the "tails" of the distribution (just the "tails" contain values close to extremes). Many other issues of climate variations become evident when we see the whole distribution rather than only mean value.

Our knowledge of the whole distribution, thus, becomes much more than desirable—it becomes necessary when we try to answer the second, more complicated question; i.e., "Is climate becoming more variable and more extreme?"

The climate trend is a basic concept of climatology; a way to express the principal long-period tendencies toward change in the climate system. The instruments to evaluate climate trends based on data are statistical calculations. These calculations are not a problem now that sufficient historical data are available and we have adequate hardware and software capacity. However, methodologically, the traditional statistical instrumentation used for trend estimation is, in fact, the way to calculate trends (changes with time) just of the mean values of some relatively short periods (say, mean values within a month, or within a season, or, eventually, within a whole year). The instrumentation is not valid to estimate climate trends when the variability values within each of these relatively short periods, taken chronologically, are monotonically changing in long period scale (decadal or century scale). Ironically, changes in variability, as well as change in extreme values, are of high interest in climatology, as indicated by the question, "Is climate being more variable and more extreme?"

What could be done to correctly assess the long period changes in the essential characteristics of climate, as opposed to—and more informatively than—mean values?

To study the whole distribution rather than mean values only, we recommend using Quantile Regression (QR) instead of the traditional statistical instruments widely used for studies of climate trends. After more than three decades of development, QR [4] is gradually becoming a fundamental tool of applied statistics. The positive prerequisite for this is that more and more commercial software has started to include this methodology in its toolboxes. The traditional regression method (often used for climate trend estimates) estimates the relationship between the average of the dependent variable and the explanatory variable. However, other aspects of the relationship—e.g., variation and skew of the distribution—are also important information. QR is designed specifically to provide a more complete picture of this relationship. QR is used in social research, economy and finance, biology, and in numerous environmental science and monitoring applications. For climate trends in particular, QR instrumentation is a way to provide a more complete picture of the trends of different quantiles (quantiles are known to be in the interval between 0 and 1).

Several publications are based on the use of QR instrumentation in climatology. Namely, our publication of 2010 [9] contains several considerations and results

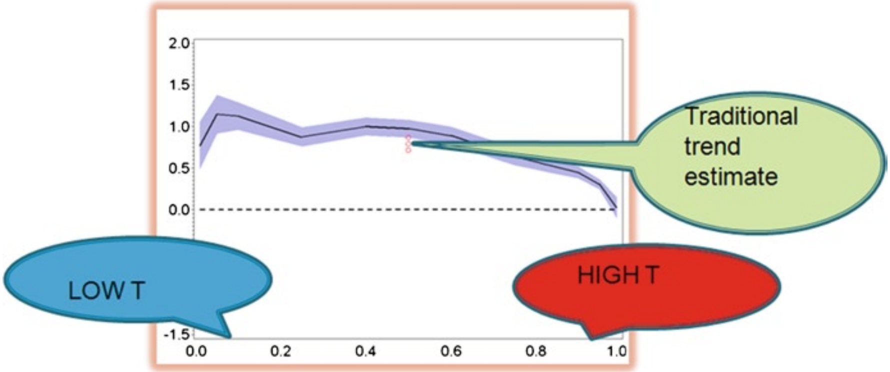

Fig. 27.1 Process diagram for climate trends of temperature. *Horizontal axis* – value of quantile between 0 and 1, *vertical axis* – value of climate trend (deg. C/10 years)

of using QR for climate trend estimation. . Other publications [5, 6, 10] use QR in different meteorological researches and applications. Before including results in this publication, it is necessary to mention that the plot of the regression coefficient (in our case, of climate trend) vs. the quantile value in the interval between 0 and 1, is called the QR process diagram. Such a quantile diagram is the result of calculating a regression coefficient for each separate quantile value, which then are plotted against quantile values on the X axis (X varies from 0 to 1). These plots are usually presented as lines within pipes, so that the pipes demonstrate the standard error intervals for the regression coefficient values. In other words, in our case, the process diagram reflects the dependency of climate trend on the quantile value, so that the value of this curve for the quantile, usually close to 0.5, is just the value of "traditionally measured" climate trend, but for quantiles different from this one, the trend values may differ essentially.

A process diagram example is presented in Fig. 27.1.

Trends for lower temperatures (quantile values lower than 0.5, and, moreover, close to 0) are evidently higher than those for higher temperatures (quantile values higher than 0.5, close to 1). For comparison, the trend value calculated by traditional techniques is shown as a dot with standard error whiskers, located about the quantile equal to 0.5. This diagram is obtained for a certain winter period temperature time series for a 35-year period, for the Saratov meteorological station. It can be interpreted so that the average winter warming at that location is ensured by the strong increase of the lowest temperature values (i.e., of the values located closest to the lowest quantile values). On the other hand, the increase of the higher temperature values (i.e., of those corresponding to relatively warm days of the winter season) is much smaller. The simple traditional trend value is close to that of the quantile value closest to 0.5. It is an aggregated, collapsed, and surely less informative climate trend, while the process diagram is a way to obtain detailed information about long-period climate processes.

Figure 27.2 contains several process diagrams for temperature time series trends of certain seasons for two meteorological stations. It is obvious that the seasonal

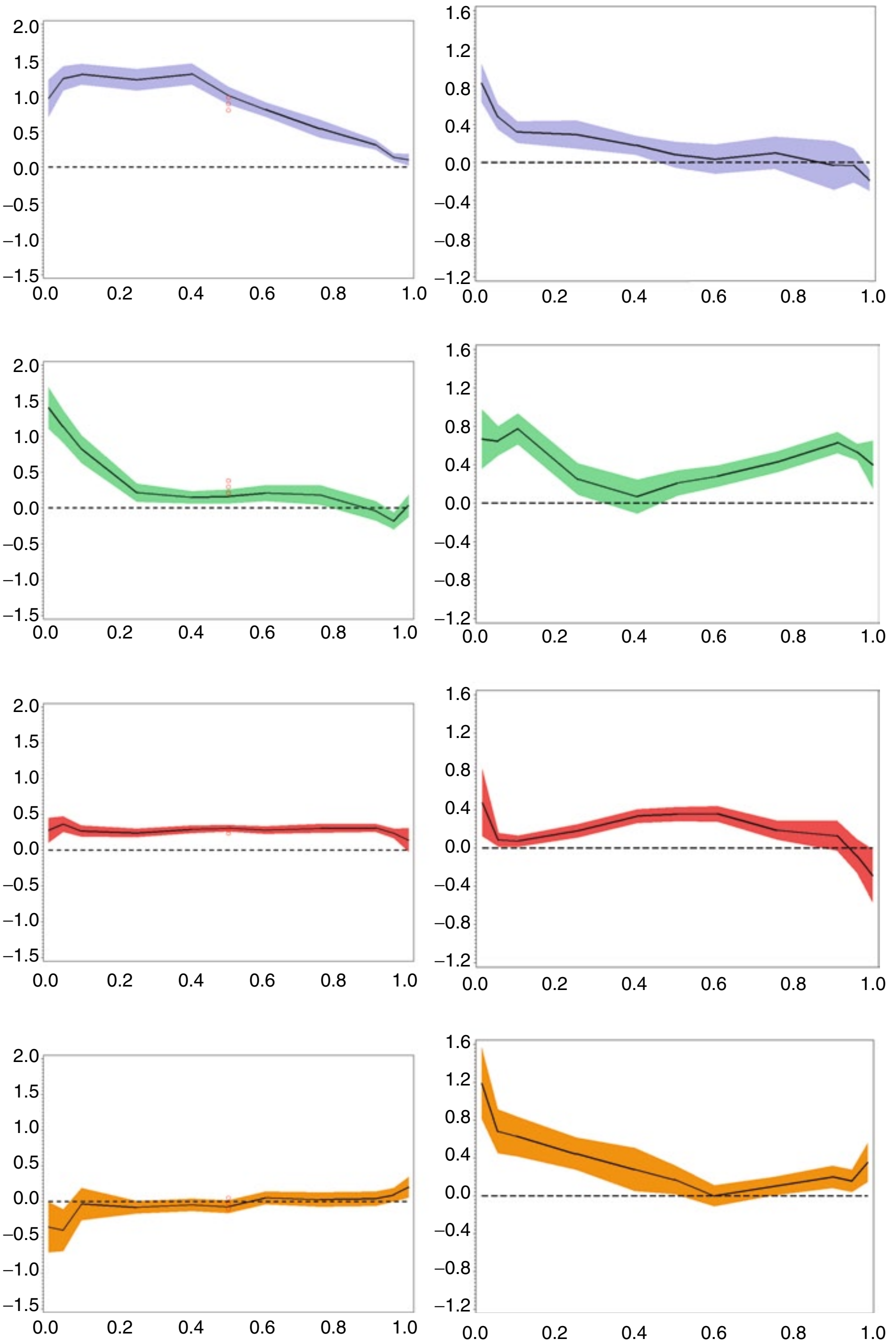

Fig. 27.2 Process diagrams for trends in temperature time series estimated by Quantile Regression. *Left* – for station Moscow (synoptic WMO index 27612), *right* – for station Khatanga (synoptic WMO index 20891). From *top* to *bottom*: winter (*DJF*), spring (*MAM*), summer (*JJA*) and fall (*SON*)

features of process diagrams differ from season to season, confirming that for European Russia winter warming is stronger than the summer warming, and each season (both in European and Asian Russia) has its own specific trends, both traditional climatologic average trends, and detailed trends estimated by QR.

QR is much more resource-consuming than traditional techniques. The QR approach also requires climate time series of high temporal resolution, because the concept of the quantile presumes the ability to rank values by some parameters, and the number of these values needs to be sufficient, for more precise ranking and further quantile and quantile regression calculations. All these factors require additional computer and human effort. But a much more detailed understanding of climate processes and of related risk is more than adequate compensation for these efforts. According to a Russian saying, " Free cheese is only in a mousetrap." And considering this, one planning to understand climate processes in detail and to make decisions to withstand climate risks, should realize that "this cheese is not free."

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Chapter 28
Climate Change: Costs of Impacts in France Preparation for the National Adaptation Plan*

M. Galliot and R. Nyer

Abstract Recorded climate warming in France was about 30% greater than average global warming in the twentieth century. Associated costs are significant, and are being absorbed by a range of areas, including biodiversity, water, health, tourism, agriculture, and transportation. Adaptive planning is critical to mitigating the impacts of climate change and is ongoing in several sectors (Climate Congress (2009) Changement climatique. Available at: http://climatecongress.ku.dk/pdf/synthesisreport/). To prepare for a national adaptation plan a consultation was carried out during 2010 in mainland France and overseas. A national plan is targeted for 2011.

28.1 Introduction

Since the 4th IPCC report, published in 2007, doubt is no longer permitted as to whether global warming is now a reality. Climate models all state that this warming will continue over the coming decades. The global warming recorded in mainland France during the twentieth century is about 30% greater than the average warming throughout the globe. The average annual temperature has risen by 0.95°C in mainland France, compared to 0.74°C globally. These values are even higher if we only concern ourselves with the second half of the twentieth century: increase of 1.1–1.5°C over the period 1950–2000. This average warming is accompanied by an increase in autumn and winter rainfall (between 5% and 35%) and a drop in summer rainfall (Fig. 28.1).

* From the ONERC reports to the Prime Minister, Minister of State on Ecology and Sustainable Development, and Parliament

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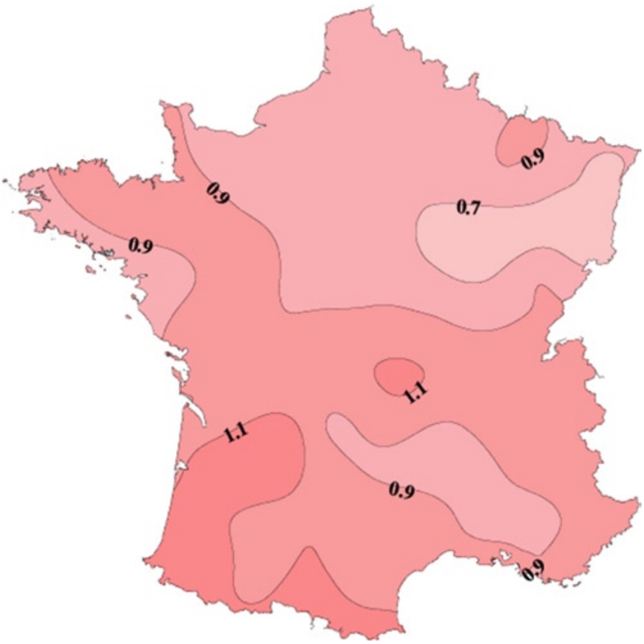

Fig. 28.1 Increase in the average annual temperature in mainland France over the period 1901–2000

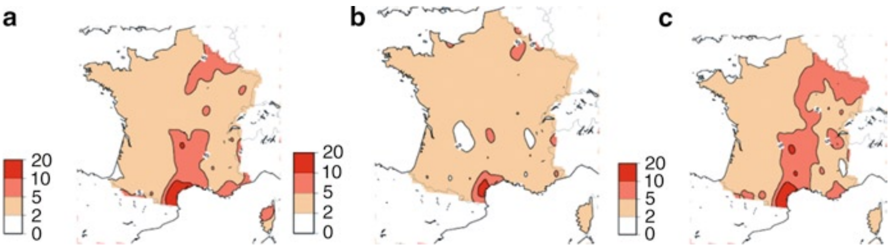

Fig. 28.2 Relationship between the number of days of summer heat wave predicted for the period 2021 and 2050 and that observed during the reference period 1961–1990. Using IPCC scenarios A1B (**a**), A2 (**b**) and B1 (**c**) (source: Météo France)

If this trend continues in the same proportions, global warming of 2°C will mean warming of almost 3°C for France, or in the most pessimistic scenario, global warming of 6°C will mean we will see warming of 8°C. Furthermore, in France, summer warming will be clearly more marked than winter warming. This confirms in particular that episodes of heatwave similar to or more intense than that of 2003 will inevitably occur much more frequently (Fig. 28.2).

The exact scale of climate change is still uncertain because it is linked to complex phenomena and to the political and technical choices that will be made.

Table 28.1 Annual costs of global impacts in the world (billions of US dollars)

	Optimistic scenario	Pessimistic scenario	Horizon
Parry et al. report [3]	1,900	2,400	2060 without adaptation
	1,200	1,500	2060 with adaptation
Stern review [2]	1,500	6,000	current and future

Numerous researchers, who met in Copenhagen in March 2009 [1] on the initiative of the International Alliance of Research Universities, highlighted that the analysis of the latest observations showed that greenhouse gas emissions were nearing the most extreme scenarios predicted by the IPCC. The climate's response is also in the upper limit of the prediction range.

The speed at which the arctic ice caps are melting has accelerated and during 2007 and 2008 the size of the ice cap at the end of summer has seen an extreme reduction in comparison to the average for the previous years. The speed at which the sea is rising is increasing, from 1993 to date, caused in large part by the increasing contribution from the melting Greenland and Antarctic ice caps. The prediction models for rising sea levels have trouble taking into account the behavior of these polar icecaps and their results are very uncertain. New estimates based on the relationship between the average global increase in temperature and the rise in sea level over the last 120 years, presuming that this relationship will stay the same in the future, suggests an increase in sea level close to or greater than 1 m by 2100.

It would appear that, in the current context, greenhouse gas (GHG) emissions cannot be sufficiently adjusted in the short term to stabilize the world's climate; consequently it has become necessary to take into account adaptation, in addition to mitigation actions (i.e. reduction in GHG emissions). Adaptation to climate change is defined as:

> …the adjustment of natural or human systems in response to present or future climatic stimuli or their effects, in order to reduce harmful effects or to exploit beneficial opportunities.

To this end, we can distinguish adaptation measures by (i) their spontaneous or planned nature and (ii) their private or public initiative.

The economic challenges of adaptation have in particular been put under the spotlight with the publication of the Stern Review in 2006 [2]: the major impacts of climate change will cost up to 20% of the world GNP (around USD 6,000 billion per year, according to the review), whereas the measures enabling them to be avoided will only cost 1–2% (i.e. between USD $300 and 600 billion per year). A recent report [3], co-authored by the President of the impact evaluation group for the last IPCC report, gives similar estimates (Table 28.1).

In addition to the economic sector, adaptation also concerns biodiversity, water resource management, and territorial governance.

Due to the inertia of climatic systems, adaptation actions will only have concrete effects in the medium or long term, but need to be taken as of today for maximum efficiency and a reduction in the scale of the impacts. Short-term mobilization and reaction to counter a medium- or long-term impact is the greatest challenge posed by adaptation.

28.2 Costs of Impacts

In March 2007, the Ministry for Ecology, Energy, Sustainable Development and the Sea (MEEDDM) formed an interministerial group under the name "Impacts of climate change, adaptation and associated costs in France," thus undertaking a project to evaluate the damage and the measures that will allow the cost of impacts to be limited.

One of the characteristics of this task resides in the fact that it is, for the most part, carried out by the services concerned, with research organization and private player collaboration. It must be considered as a stage in an ambitious public action gauging process: it leads to temporary results that remain open to discussion, for development in later stages.

28.2.1 Methodological Frameworks

The decision has produced sectoral evaluations at Horizons 2030, 2050, and 2100, without wanting to aggregate the results. At this stage, the thematic works have not been designed to be exhaustive: only certain impacts have been assessed in a quantitative fashion.

The group chose to work from the IPCC A2 and B2 scenarios, in accordance with the simulations created by CNRM/Météo-France using the Arpège-Climate model. A2 is a rather pessimistic scenario, B2 an optimistic scenario: these two scenarios are generally those adopted in climate change impact analysis.

In the absence of a long-term socioeconomic outlook for France per region and per sector, it was decided to work using the current French socioeconomic situation (scenario known as "constant economy"). This choice allows the impact of climate change to be isolated from that of other developments and does not add macroeconomic uncertainties to uncertainties relating to climatic aspects. Nevertheless, this choice remains restrictive and limiting for some sectors, for which a socioeconomic change is already anticipated or for which these changes constitute a determining factor in the vulnerability to climate change.

28.2.2 Scope and Results of Thematic Works

Only a limited number of sectors have been studied and within these the analysis only concerned a selection of climate change impacts. The estimated costs must be considered as rough estimates, due to the limits of the methodologies used and the non-exhaustive nature of the evaluations carried out. The detail of the quantitative evaluations is recorded in the general report.

28.2.2.1 Water Resources

If we consider demand as being stable, a deficit of two billion m^3/year in meeting the current needs of industry, agriculture (irrigation) and drinking water supply will be seen at Horizon 2050. The projections indicate that the zones most affected will be those already concerned by structural deficits. Estimating the compensation for the potential deficit in water resources at Horizon 2050 only represents a "visible" part of the adaptations needed and an extremely partial evaluation of the need to adapt water-related activities. All sectors will be affected by this change, which will mean an increase in conflicts of use, a decrease in water quality and therefore a disturbance to aquatic ecosystems or part of the water resources. The adaptation of each sector to climate change will include better management of water consumption: adaptation of water demands and requirements is a priority theme. As to the adaptation of the offer, this will have to come within a planned adaptation, in order to study the impacts in advance. The evaluation of the potential cost of these adaptation measures can only be made via local enquiries. They may represent very high operating investments and expenditures.

28.2.2.2 Natural Hazards and Insurance

The analysis concerned four specific types of hazard: floods, coastal hazards, clay shrinkage and swelling, and gravitational hazards (avalanches, mudslides, rockfalls, etc.). For example, at a constant rate of urbanization, the average annual damage to dwellings generated by the risk of clay shrinkage and swelling could exceed EUR 1 billion in 2100. This cost could be multiplied by a factor of 4–5 if we take into account urbanization in risk zones. In the absence of adaptation, the impacts of coastal hazards (erosion and submersion), will eventually concern several hundred thousand people and the destruction of housing will cost, for the Languedoc-Roussillon region alone, several tens of billion euro over a century. The cost of damages linked to floods caused by rivers breaking their banks could also be significant with, in this case, major uncertainties remaining as to the expected impact and the difficulty in distinguishing the costs resulting from climate change alone. As to the cost relating to gravitational hazards, this has not been assessed, because of a need for more information. However, the heavy impact on society of catastrophes arising from these hazards should be underlined, as these can lead to the loss of human life and very high localized costs.

28.2.2.3 Biodiversity

Even though it is sometimes difficult to isolate the impacts of climate change from other pressures suffered by ecosystems, and even though the problems are very different depending on the ecosystem and the species concerned, signs of changes in biodiversity attributable to the gradual modifications caused by climate change can already be seen. Biodiversity is directly affected by the changes in temperature and rainfall amounts in particular, but the indirect effects could be at least as high. It is therefore essential to know more about the cross effects of climate change impacts on one hand, and spontaneous or planned adaptations on the other, in order to prevent negative consequences for biodiversity. Furthermore, the preservation of natural ecosystems and their resilience may also constitute an adaptation action (combating flooding, for example). The economic assessment of biodiversity losses is based on the concept of ecosystem services. This approach, applied to coral ecosystems and non-goods services provided by forests shows clearly negative impacts. On a more global scale, significant economic losses related to the reduction, and even disappearance, of regulation services are to be expected, in particular in the second half of the twenty-first century. Giving priority to territorial governance may enable the better integration of biodiversity protection and the various challenges to be met, on relevant spatial scales.

28.2.2.4 Health

The economic assessment task concerned the impact of two major extreme events (heatwave in 2003 and flooding of Gard in 2002). The measurement of the impact of the heatwave took into account the real costs and the costs saved for health insurance, the indirect costs (loss of human life, non-productive time) and the intangible costs (estimated value of the loss of quality of life and suffering linked to a decline in health). If the impact for health insurance does not seem significant, the global cost for society as a whole is nevertheless considerable. We estimate the value lost by our society because of the 2003 heatwave as being a little more than EUR 500 million on the basis of an average loss of 1 year of lifespan.[1] During the floods, three major danger-to-health phases were noted: an immediate danger phase (injury and death), a short-term danger phase (risks of infection), and a danger phase regarding the psychological problems relating to post-traumatic stress. The group's evaluation task concentrated on this last phase. With regard to the Gard floods, the cost of taking care of people presenting psychological disorders has been estimated at approximately EUR 234,000 (for 953 people). This is a low estimate, since it only concerns the cost of treatment (the indirect and intangible costs not having been calculated).

28.2.2.5 Agricultural Sector

The growth models for the field crops used show an increase in yield in response to climate change (notably for wheat up to horizon 2100). This increase does not take

[1]Calculated in accordance with the recommendations of the Boiteux report (2001)

into account inter-annual variability and the drop in water availability. The inclusion of these variability factors, which are still badly integrated into the growth models, could enable the results to be refined and the anticipated increase in yield to be moderated. For example, increased events like the 2003 heat wave could, in 2100, represent a cost of up to more than EUR 300 million per year for a crop such as wheat in the absence of any adaptation measure. Viticulture will also be affected by climate change, with high territorial differences and effects on the quality of the wines. In the case of meadows, the exercise carried out for the peri-Mediterranean area gives a loss-compensation cost of EUR 200 million per year over the second half of the twenty-first century. It is therefore necessary to adapt to these forecast changes as of now.

28.2.2.6 Forest Sector

An increase in productivity (volume of wood) is expected in the short and medium terms because of the increase in temperatures and rates of CO_2 in the atmosphere. Therefore, the additional annual gross production will reach almost 30 million m^3 in 2050. Nevertheless, over this same period, the expected gains in productivity are on the same scale as possible losses through wilting, fire, and drought. After 2050, the trend will be unfavorable because of water stress, particularly in the south of France, with an increased risk of drought and fire, suggesting clearly negative impacts in the long term. In order to compensate for these effects, adaptation by the forest sector will have to make all parties in the field play their part. With regard to forest fires, a study led by the interministerial Mission on the risk of climate change-related fires is currently underway. According to the initial results, the expected climate change will be accompanied by an increased hazard in areas that are already at risk (where systems protecting forests from fires are in place), as well as by a regional spread (towards the North and at altitude) of the forest fire hazard.

28.2.2.7 Energy

Climate change will have consequences on demand, with a drop in energy consumption in winter, but an increase in summer because of the need for air conditioning in housing and vehicles. The economic assessment of these impacts reveals an energy saving trend of around 3% in the constant economy scenario; i.e., 1.8–5.9 Mtoe/year according to the scenarios and horizons, but the spontaneous development of residential and automotive air conditioning will cut global warming-related energy savings by half. In terms of electricity production, because of the restrictions relating to water resources, we must expect a drop in production of around 15% from hydroelectric plants, for which water is the raw material, and yield losses for production and energy transport infrastructures.

28.2.2.8 Tourism

The results provided by a study carried out by the *Centre International de Recherche sur l'Environnement et le Développement* (CIRED – International Research Centre on Environment and Development) and Sogreah, based on the summer tourist comfort index (ICT), highlight a drop in summer climate comfort throughout mainland France, with maximum temperatures reached becoming too high to afford tourists maximum comfort. This deterioration is less marked in the Northern half of France (Northwest Coast specifically), as well as in certain mountainous areas (particularly in the Alps). By 2100, a significant impact on summer turnover is to be expected, because of a drop in attractiveness to tourists, except in the north of France and certain areas in the Alps. On the other hand, an improvement in conditions will be seen in the other seasons. With regard to winter sports, an OECD study in 2006 indicated that, in the Alps, the reduction in snow cover will reduce the reliability of the depth of snow. In the French Alps, 143 skiable resorts currently have a low snow depth. In the event of warming by +1°C, this will be the case for only 123 resorts; for 96 resorts if warming reaches 2°C and for only 55 resorts in the event of warming by 4°C. In a general fashion, this work indicated that, in all geographical areas of mainland France, the tourism sector must adapt to future indications of climate change in order to limit the negative impacts and seize the potential opportunities.

28.2.2.9 Transport Infrastructures

The predicted climate change could mean adaptations are required at road infrastructure level. Although the 2003 heat wave did not seem to cause generalized disorders that call into question the permanence of the roadway or civil engineering structures, the effects of repetitive periods of heat wave are not known at this time. As far as the risk of permanent marine submersion linked to an overall rise in sea levels by one meter is concerned, this would represent a property cost, for the mainland A-roads (excluding motorways and other roads), excluding loss of use and outside of the "network" effect (for example the submersion of a limited length of road could cause an entire section to be unavailable but only the property value for the submerged length has been calculated) that falls in a range between EUR 500 million and 1.2 billion. It could reach EUR 2 billion if the current protections prove to be insufficient. For reasons of data availability, infrastructures outside the public national network and port, rail, and river infrastructures have not been studied.

28.2.2.10 Territories

The words specifically concerned the question of the pertinent scale of analysis, sectoral interaction on a territorial scale, and the concept of transition towards change. The importance of the time interval needed for what we could call "the vulnerability apprenticeship" was highlighted. This conversion will last as long as the public's likely to be affected by the impacts of climate change are not, on the face of it, uniform. For these reasons, the informing, awareness raising, and mobilizing of players and populations in relation to climate change and adaptation constitute fundamental aspects. In addition, it has been proved that adaptation will above all include a better knowledge of climate change and its challenges, with organization of skills also playing a major role. In view of these observations, it is necessary to take the measure of social rhythms useful for making concrete the common objective of a non-fractured development towards new lifestyles.

28.2.3 Analysis Elements

The works carried out highlight the costs, but also the benefits linked to climate change in mainland France, depending on the sector considered, climate scenarios and time horizon. For some sectors, we will see both costs and opportunities depending on the impact studied, so much so that it is sometimes difficult to determine the sign of the "net" impact of climate change. Nevertheless, in view of the qualitative and quantitative analyses carried out by the study groups, we can expect a negative global impact from climate change; the costs could reach several hundreds of millions of euro per year for various sectors if no adaptation is undertaken.

Seen as an additional mitigation policy, adaptation will allow the costs of climate change impacts to be limited significantly, and even transformed into opportunities in some cases. If spontaneous adaptation can already limit the negative impacts of climate change, we should note that unorganized adaptation could also increase them or limit benefits: this is the case with energy, with the spontaneous development of air conditioning, which plays a part in significantly increasing energy consumption in summer, and therefore greenhouse gas emissions; or for agriculture, where a spontaneous increase in irrigation is incompatible with the reduction in water availability. This highlights the importance of coordinating and organizing adaptation in order to avoid these pitfalls.

The impacts of climate change will not be spread evenly or fairly across the territory:

- From a geographical point of view, some regions could find themselves severely affected by the changes, whereas others will be less so and may even turn this to good account. These differences are due as much to climatic hazards as to territorial geographical and socioeconomic characteristics likely to influence the vulnerability of systems;
- From an individual point of view, players will not be equally subject to climate change. Depending on the sector of economic activity and the social vulnerability of households, the effects will not be redistributed in the same way. The most disadvantaged individuals will probably be the most and the quickest affected by the impacts of climate change.

Adaptation to climate change must therefore be contextualized and make sure inequalities in view of risk are reduced.

Several uncertainties remain over what the consequences of climate change will be: it is therefore necessary to plan governance methods that can be both planned for the long term and progressive over the short term.

28.2.3.1 Identified Lines of Adaptation

While the works were mainly focused on the impacts of climate change, some lines of adaptation were listed or suggested. These options do not, at this stage, constitute recommendations, but rather lines to be considered within the framework of adaptation planning studies. Their relevance, efficiency, and feasibility must be studied in an integrated fashion, in particular by taking into account local context.

Some non-exhaustive examples of lines include:

- General: organize availability of climate model results – in particular, the collapses on a local level – and impact studies.
- Water: implement alternative agricultural systems that are more robust and less demanding on water resources (already included in Objective Earth 2020).
- Natural hazards: take into account climate change in planning and development documents.
- Biodiversity: enhance protected spaces as preferred areas for observing the impacts of climate change and monitoring adaptation strategies.
- Health: integrate health risks of climatic origin in basic and ongoing training for healthcare professionals.
- Agriculture: diversify the crop systems, allowing *evasion*, *avoidance*, and *tolerance* to be combined.
- Energy: ease the development of a building and urbanism framework that reduces the demands on energy, particularly that of air conditioning.
- Tourism: develop four-season tourism, in order to reduce the dependence on snow.

28.2.3.2 Perspectives

For reasons of feasibility and data availability, some points could not be tackled. These choices do not prejudge the importance of the impacts of climate change on these sectors, which merit being treated in future stages.

The fields that were not handled in this study and that must form the subject of specific attention in future stages were as follows:

- Urbanism, as well as the air, port, river and rail sectors
- The maritime, fishing, and aquaculture sector
- Tertiary sector activities (other than the tourism sector)

- Industrial sector activities (other than the energy sector)
- The impacts of climate change on cultural heritage

The integration of overseas territories in the quantitative evaluation of impacts and adaptation measures constitutes a major priority. The problems of climate change in the overseas departments and collectivities and in New Caledonia are different from those affecting mainland France. This involves, as of now, works resulting in particular in a better knowledge of the development of climatic parameters and their consequences in these areas.

The crossover knowledge and observation requirements have been identified in order to advance understanding of the economic impacts of climate change:

- Improve knowledge about climate changes, in particular for the hazards that remain subject to major uncertainty:
  - The change in rainfall patterns
  - The rise in sea levels
  - The consequences of climate change on the hydrological regime
  - Highly localized climatic hazards; i.e., gravitational hazards
  - Changes to sun and wind patterns
  - Changes to the physico-chemical characteristics of marine habitats
- Improve the characterization of certain hazards – droughts or heat waves, for example – in terms of intensity or even territorialization.
- Produce territorialized data, whether this is for hazards, models, climate scenarios, or socioeconomic development scenarios.
- Improve the characterization and quantification of non-goods impacts.
- Integrate the problems of adaptation and mitigation, via research aimed at better identifying their synergy and conflicts.
- Improve understanding of the spontaneous adaptation behavior of the various players.
- Lead a discussion on the feasibility and acceptability of implementing planned adaptation measures.
- Continue work on adaptation costs, little touched on here, on the junction between the economics of uncertainty and long-term economics, and involving the availability of economic analysis tools for adaptation.
- Improve the inclusion of sectoral interactions: the impacts of climate change on one given sector will in fact be largely influenced by the impacts affecting other sectors.
- Launch a global discussion and a planning effort with regard to the questions of water availability and use within the context of climate change.
- Continue a multi-risk and multi-sector discussion on adaptation.

Finally, in general, the steps must be produced on other scales, in particular for local collectivities.

28.3 Preparation for the National Climate Change Adaptation Plan

France's adaptation to climate change has become a major issue, which calls for a national mobilization. This adaptation should now be viewed as an essential supplement to the mitigation activities already underway.

Article 42 of the 2009-967 framework law of 3 August 2009 relative to the implementation of the Grenelle Environment Forum provides for a national adaptation plan for different sectors of activity to be prepared by 2011 at the latest. It will bring together ambitious approaches on subjects as diverse as the fight against flooding and the adaptation of coastal zones, the spread of forests, water issues, and adapting the economy.

The Minister of State for the Economy, Energy, Sustainable Development and the Sea, responsible for green technologies and climate negotiations, opted for an extensive consultation exercise prior to the development of the national adaptation plan launched in December 2009.

The aims of the consultation exercise chaired by the French Observatory for the Impacts of Global Warming (ONERC) were to:

- Mobilize public authorities as a whole, private stakeholders, and civil society so that adaptation is seen as being on a par with mitigation and to raise awareness of the issues involved.
- Gather advice and recommendations to define a national climate change adaptation plan as provided for under article 42 of the framework law for implementing the Grenelle Environment Forum.

28.3.1 The National Consultation Phase

This phase was organized on the basis of the Grenelle Environment Forum colleges – elected representatives and local authorities, the state, employers, staff unions, and associations were divided into three working parties:

- Group 1 addressed the cross-cutting themes of water, biodiversity, health, and natural hazards.
- Group 2 addressed sectoral themes of agriculture/forestry/fishing, energy, tourism, transport infrastructures, town planning, and the built environment.
- Group 3 addressed governance, knowledge information/education, and funding.

National groups met in four plenary sessions between January and May 2010 and the report from the working parties was submitted to the Secretary of State for Ecology on June 15th. This report contains 202 suggestions and was made available to the public on the ONERC website.

28.3.2 Consultation with French Overseas Regions

In parallel with the national consultation, consultations also took place in the four French overseas regions. Each region had a free choice in the format of its consultation. Reports were submitted at the end of June to the Secretary of State for Ecology.

28.3.3 The Final Stages

In September-October, the reports from national groups and overseas regions were submitted for regional consultation.

From 13 September to 15 October, the opinion of the general public was sought in an electronic consultation on the Internet. Over 4,000 people responded to the consultation, demonstrating French interest in this work.

The information gathered during this consultation will provide the basis for the development of the national adaptation plan which will be adopted in 2011 in accordance with the framework law for implementing the Grenelle Environment Forum. A final round table took place on November 23, 2010, chaired by the Minister of Ecology, Sustainable Development, Transportation, and Housing, who launched work for the national plan for adaptation. All the ministerial departments are mobilized to put forward measures to be implemented over the next five years to adapt France to the effects of climate change.

Acknowledgements All the ONERC reports (summary and full reports), from which this text has been extracted, are available on the ONERC website: www.onerc.gouv.fr.

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Chapter 29
Climate Change

Global, Regional, and National Dimensions

A.A. Hady

Abstract Solar activities have had notable effect on paleoclimatic changes. Contemporary solar activities are weak and hence expected to cause global cooling. Prevalent global warming, caused by buildup of greenhouse gases in the troposphere, seems to exceed this solar effect. This paper discusses this issue.

The River Nile is the principal source of water to Egypt. Hence the climates of the Nile Basin are of special importance. Egypt and the nine other countries that share the Basin need to develop a regional circulation model that would enable them to forecast future climate changes.

Recent changes in climate parameters over Egypt and its impacts have been assessed, and efforts towards mitigation and adaptation to climate change were reported in the national communication to the United Nations Climate Change Conference (COP) in 2009.

29.1 Introduction

The United Nations Secretary General Ban-Ki moon, at the United Nations Climate Change Conference (COP) -14, in Pozna (December 2008),[1] stated:

> Climate change has long since ceased to be a scientific curiosity, and is no longer just one of many environmental and regulatory concerns. It is the major, overriding environmental issue of our time, and the single greatest challenge facing decision makers at many levels.

[1] The 14th session of the conference of parties to the UN framework convention on climate change.

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NATO Science for Peace and Security Series C: Environmental Security,
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Climate change has become a prominent item on the agenda of world concerns. It is a growing crisis with economic, health and safety, food production, security, and other dimensions. There is alarming evidence that important tipping points, leading to irreversible change in major earth systems and ecosystems, may already have been reached or passed. The change of climate is pushing many earth systems towards critical thresholds that will alter regional and global environmental balances and threaten the world at multiple scales.

Questions are being asked and hypotheses are being proposed to identify the real forces that drive global climate change. Is it a geological issue or cosmological issue or an issue of social behavior? In this paper we discuss solar activities and their effects on climate change. The regional and recent changes in climate parameters over Egypt and their impacts will be addressed in this paper.

29.2 Deep Solar Minimum of Cycle 23

Solar activity affects the climate but seems to plays only a minor role in the current global warming. For example, the Earth's temperature has risen perceptibly in the last 30 years while solar brightness has not appreciably increased [15, 19]. Average solar activity has declined rapidly since 1985 and cosmogenic isotopes suggest a possible return to Maunder Minimum conditions within the next 50 years.

This section examines the deep minimum of solar cycle 23 and its likely impact on climate change. In addition, a source region of the solar winds at solar activity minimum, especially in solar cycle 23, the deepest of the last 100 years, has been studied. Is this episode comparable to the Maunder Minimum or is it like the Dalton Minimum? Furthermore, the near-future solar cycle 24 and prediction of its conditions are presented. Solar cycle 23 started in April 1996 and had its peak in early 2000 and 2001. The decline phase of this period extended from 2002 until December 2009, which is the longest decline phase in the last 23 solar cycles. Solar cycle 24 started in 2009. It was a late starter, about 3.5 years later than the average of the strong cycles in the late twentieth century and almost 3 years later than the weak cycles of the late nineteenth century. For more details about solar cycle 23 activities and its statistics, see, for example, Hady [6, 8] and Hady and Shaltout [7]. Figure 29.1 shows the length of the past five solar cycles (19, 20, 21, 22, 23), in the graph on the left and the cycle 23 behavior alongside the cycle 24 prediction on the right. These graphs were created by the Marshall Space Flight Center, NASA. We may observe that solar cycle 23 extended for 13.5 years starting in April 1996, and it is a very weak cycle compared with solar cycle 19 [11].

The monthly and yearly mean of sunspots during solar cycle 23 and its decline phase until December 2009 are given in Table 29.1. The data used to prepare Tables 29.1 and 29.2 were obtained from Kandilli Observatory, Bogazici University, Turkey.

From Table 29.1 we note the spotless days during years 2007, 2008, 2009. During 2008 there were no sunspots observed on 266 days of the year's 366 days (73%),

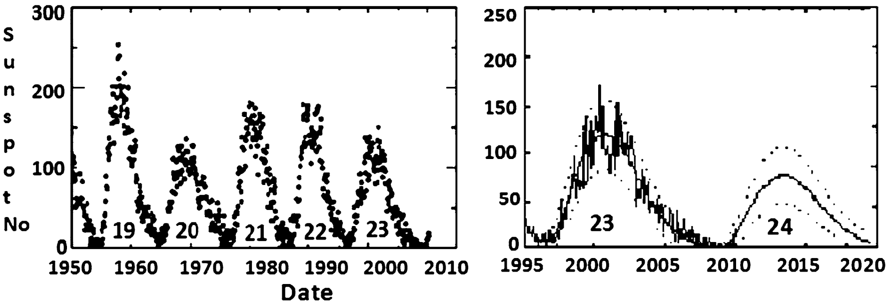

Fig. 29.1 Sunspot cycles and cycle 24 prediction

and during 2009, 274 of 365 days were spotless (75% spotless days). These represent the deepest minimum of the twentieth century. The sun is in a phase of unusually low activity, as indicated by comparing sunspots numbers and spotless days with recorded observations over a long period during the twentieth century. Figure 29.2 shows the spotless days in years of the twentieth century.

Monthly and yearly means for the flare index during the maximum activity of solar cycle 23, and its decline phase until December 2009, are given in Table 29.2. Data in Table 29.2 show that the yearly means of the flare index are less than 0.5 starting in 2006, which means that reduced solar activity begins in 2006.

Prediction of the behavior of a sunspot cycle is fairly reliable once the cycle is well underway. A number of techniques are used to predict the amplitude of a cycle during the time near and before the sunspot minimum. Relationships have been found between the size of the next cycle maximum and the length of the previous cycle, the level of activity at sunspot minimum, and the size of the previous cycle. The method used for solar cycle predictions depends on Feynman and Wilson's methods [9, 10, 22]. We shall show only the statistical results of our solar cycle predictions compared with all solar cycles as given in Table 29.3.

From the tables and figures we can conclude that solar activities have rapidly declined beginning about 30 years ago and will continue to decline for the next 50 years. Solar activities have had notable effects on paleoclimatic changes. Surface warming and the solar cycle in times of high solar activity are on average 0.2°C warmer than in times of low solar activity. Prevalent global warming, caused by buildup of greenhouse gases in the troposphere, seems to exceed this cooling solar effect. Figure 29.3 compares solar cycle variations, earth surface temperature, and CO_2 variability over the past 150 years. We notice that parameter variation was consistent until 1960. There is no agreement between solar cycle variations and Earth's surface temperature after CO_2 began increasing dramatically in 1960.

The scientific consensus is that solar variations do not play a major role in determining present-day observed climate change, but did play a major role in paleoclimatic changes; for example, climate cooling during the Maunder Minimum (1645–1710), and the Dalton Minimum (1797–1825) was due to the collapse of solar activity.

Table 29.1 Monthly and yearly means of sunspot numbers of solar cycle 23

Year 2001 is the maximum solar activity of cycle 23												
Monthly means:	95.6	80.6	113.5	107.7	96.6	134.0	81.8	106.4	150.7	125.5	106.5	132.2
Yearly mean:	110.58											
Year 2003 is the year of starting decline phase of cycle 23												
Monthly means	79.7	46.0	61.1	60.0	54.6	77.4	83.3	72.7	48.7	65.5	67.3	46.5
Yearly mean	63.57											
Year 2006 is the year of starting solar minimum of cycle 23												
Monthly means	15.3	4.9	10.6	30.2	22.3	13.9	12.2	12.9	14.4	10.4	21.5	13.6
Yearly mean	15.16											
Year 2007 continues solar minimum of cycle 23												
Monthly means	16.8	10.7	4.5	3.4	11.7	12.1	9.7	6.0	2.4	0.9	1.7	10.1
Yearly mean	7.5											
Spotless days	149 of 365 days (41% spotless days)											
Year 2008 continues solar minimum of cycle 23												
Monthly means	3.3	2.1	9.3	2.9	3.2	3.4	0.8	0.5	1.1	2.9	4.1	0.8
Yearly mean	2.85											
Spotless days	266 of 366 days (73% spotless days)											
Year 2009 continues solar minimum of cycle 23												
Monthly means	1.5	1.4	0.7	0.8	2.9	2.9	3.2	0.0	4.3	4.6	4.2	10.6
Yearly mean	3.1											
Spotless days	274 of 365 days (75% spotless days)											

Table 29.2 Monthly and yearly flare index of solar activity full disk of the solar cycle 23

Year 2001 is the maximum solar activities of cycle 23												
Yearly mean	6.80											
Monthly means	2.76	1.25	7.65	10.20	2.89	4.86	1.84	6.38	11.77	9.50	10.95	11.39
Year 2003 is the year of starting decline phase of cycle 23												
Yearly mean	3.46											
Monthly means	2.69	1.55	3.33	2.62	4.35	4.54	2.55	1.59	0.77	12.11	4.53	0.68
Year 2006 is the year of starting solar minimum of cycle 23												
Yearly mean	0.54											
Monthly means	0.03	0.00	0.11	0.53	0.03	0.01	0.28	0.14	0.19	0.05	0	4.89
Year 2007, continuous of minimum of cycle 23												
Yearly mean	0.47											
Monthly means	0.49	0.01	0.01	0.02	0.24	1.53	1.16	0.21	0.00	0.00	0.01	1.88
Year 2008, continuation of minimum of cycle 23												
Yearly mean	0.03											
Monthly means	0.05	0.00	0.20	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00
Year 2009, continuation of minimum of cycle 23												
Yearly mean	0.027											
Monthly means	0.04	0.00	0.03	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.20

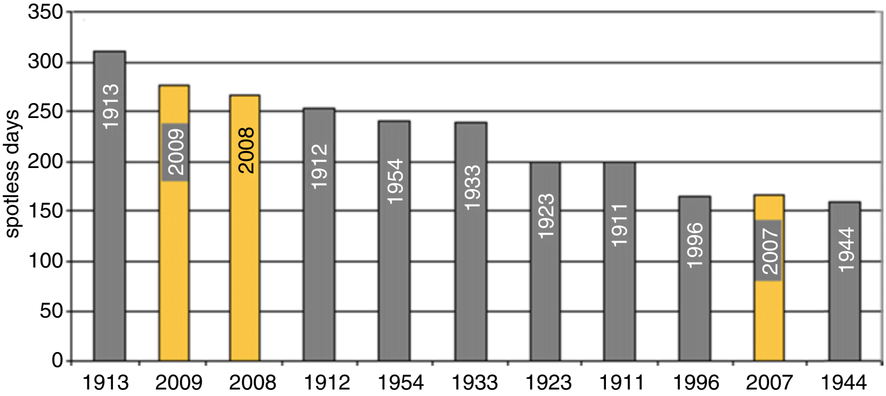

Fig. 29.2 Sunspot counts for spotless years during the twentieth century. The years 2007, 2008, and 2009 are the years of minimum of solar activity in cycle 23

Due to the paucity of sunspots during the Maunder Minimum, ^{14}C data provides evidence for the presence of solar cycles and their duration. According to Makarov and Tlatov [17], the duration of solar cycles averaged 20 years in the Maunder [1]. In Fig. 29.4, ^{14}C Count Variation in the bi-annual rings of the pine-trees from the South Urals for 1600–1730 are shown; the solar minimum is marked with vertical lines. The numbers along lower part of the figure are the length of the solar cycles from minimum to minimum, measured in years.

To compare the start of the Maunder Minimum with current day minimum, Watts Anthony [20] remarked that the maximum of Solar Cycle 24 would be in 2015; that is, 15 years after the peak of the preceding cycle. There is also a parallel in the way that the ^{14}C is climbing above the peaks of the previous minimum, as it is today with the Oulu neutron count. Neutron count tends to peak a year after solar minimum, so a neutron peak in 2010 is consistent with solar minimum in 2009. From Fig. 29.4, a repeat of the Maunder Minimum can be expected; the neutron flux will remain well above the levels reached in the minimum of the second half of the twentieth century. Activity and timing of the current minimum, as well as the timing of the Solar Cycle 24 maximum in 2015, is consistent with the start of the Maunder Minimum. There is no data to date which diverge from the pattern of the start of the Maunder Minimum [12].

Is a repeat of the Dalton Minimum possible? This question was asked after the deep solar minimum of cycle 23, which lasted 13.5 years. Solar cycle 24 was a late starter, about years later than the average of the strong cycles in the late twentieth century and almost 3 years later than the weak cycles of the late nineteenth century. Figure 29.5 shows the similarity between solar cycle behavior during the Dalton Minimum years and the behavior of solar cycles 22 and 23, as well as the behavior predicted for solar cycles 24, 25, and 26 [1, 21].

Table 29.3 Sunspot minimums and maximums for each solar cycle

Sunspot cycle number	Year of min	Smallest smoothed monthly mean	Year of max	Largest smoothed monthly mean	Rise to max (Years)	Fall to min (Years)	Cycle length (Years)
1	1755.2	8.4	1761.5	86.5	6.3	5.0	11.3
2	1766.5	11.2	1769.7	115.8	3.2	5.8	9.0
3	1775.5	7.2	1778.4	158.5	2.9	6.3	9.2
4	1784.7	9.5	1788.1	141.2	3.4	10.2	13.6
5	1798.3	3.2	1805.2	49.2	6.9	5.4	12.3
6	1810.6	0.0	1816.4	48.7	5.8	6.9	12.7
7	1823.3	0.1	1829.9	71.7	6.6	4.0	10.6
8	1833.9	7.3	1837.2	146.9	3.3	6.3	9.6
9	1843.5	10.5	1848.1	131.6	4.6	7.9	12.5
10	1856.0	3.2	1860.1	97.9	4.1	7.1	11.2
11	1867.2	5.2	1870.6	140.5	3.4	8.3	11.7
12	1878.9	2.2	1883.9	74.6	5.6	5.7	10.7
13	1889.6	5.0	1894.1	87.9	4.5	7.6	12.1
14	1901.7	2.6	1907.0	64.2	5.3	6.6	11.9
15	1913.6	1.5	1917.6	105.4	4.0	6.0	10.0
16	1923.6	5.6	1928.4	78.1	4.8	5.4	10.2
17	1933.8	3.4	1937.4	119.2	3.6	6.8	10.4
18	1944.2	7.7	1947.5	151.8	3.3	6.8	10.1
19	1954.3	3.4	1957.9	201.3	3.6	7.0	10.6
20	1964.9	9.6	1968.9	110.6	4.0	7.6	11.6
21	1976.5	12.2	1979.9	164.5	3.4	6.9	10.3
22	1986.8	12.3	1989.6	158.5	2.8	6.8	9.7
23	1996.4	8.0	2000.3	120.8	4.0	10.0	13.5
Author's estimation of cycle 24							
24	2009.96	9.0	2015.2	105.0	5.24	7.8	13.04
Mean Cycle Values		6.1	113.2		4.7	6.3	11.0

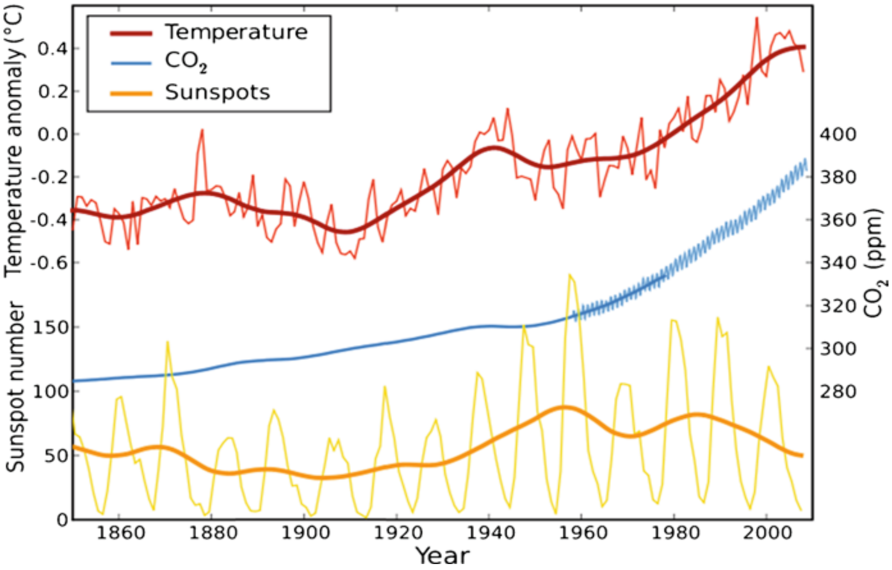

Fig. 29.3 Temperature, Co2 concentration in the troposphere, and sunspot variations from 1850 to 2010

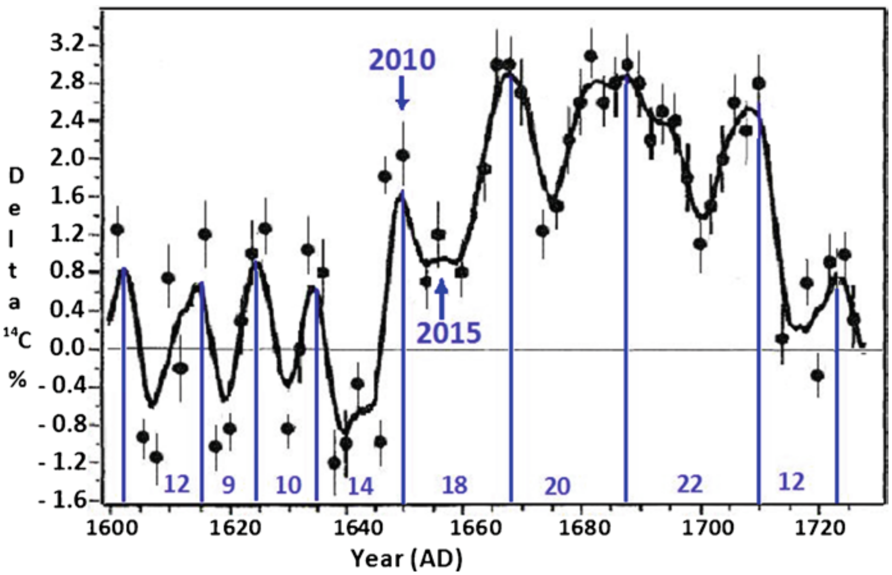

Fig. 29.4 Solar cycles during the Maunder Minimum. The solar minimum is marked with vertical lines. The numbers along the lower part of the figure are the length of the solar cycles from minimum to minimum in years. The comparison with 2010 and 2015 was marked by Watts [20]

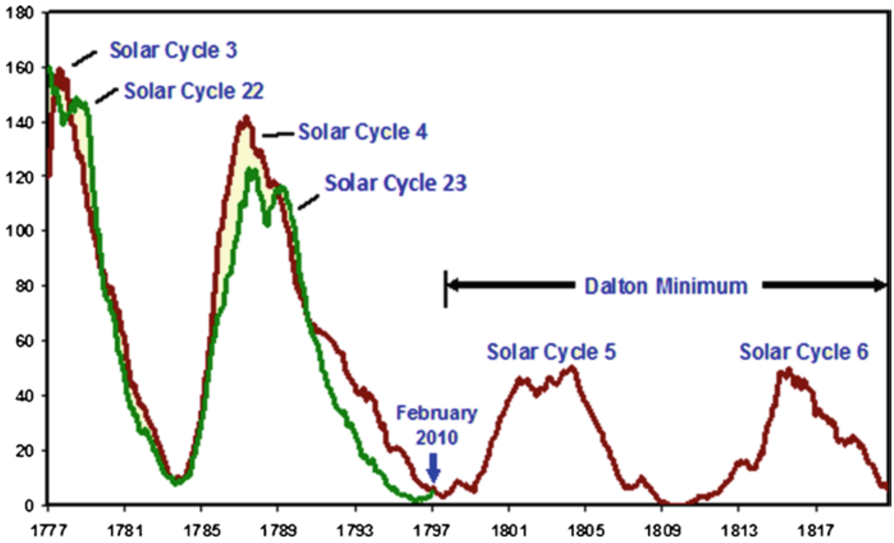

Fig. 29.5 The Dalton Minimum era and solar cycles 22 and 23 are overlaid on solar cycles 3 and 4 to show their similarity

We can conclude that while solar activities have had notable effects on paleoclimatic changes, and though contemporary solar activities are weak and hence expected to cause global cooling, prevalent global warming, caused by buildup of greenhouse gases in the atmosphere, exceeds this solar effect.

29.3 Regional Climates of the Nile Basin: Past and Future

The River Nile runs in a south to north alignment for 35° of latitude, from Lake Tanganyika (Lat 4°S) to the Mediterranean (Lat 31°N). Its basin is shared by ten countries: Zaire, Burundi, Rwanda, Tanzania, Uganda, Kenya, Eritrea, Ethiopia, Sudan, and Egypt, and spans a very wide spectrum of climates from humid tropics to deserts [14].

The Nile has a very complex geological history, but its present form with its summer floods and diverse sources is relatively recent (10,000–20,000 years) (see Said [18] for details). Climate changed dramatically during that period. From 16000 BCE until now, the climate has changed a few times. Figure 29.6 shows maps of the expansion of the Sahara around 16000 to 7000 BCE [2]. Great lakes that previously existed in the present-day desert regions of Mauritania, Chad, northeast Ethiopia, or southern Africa dried up within one or two millennia; dune massifs advanced several hundred kilometers southwards to the regions where precipitation currently borders on 800 mm/year.

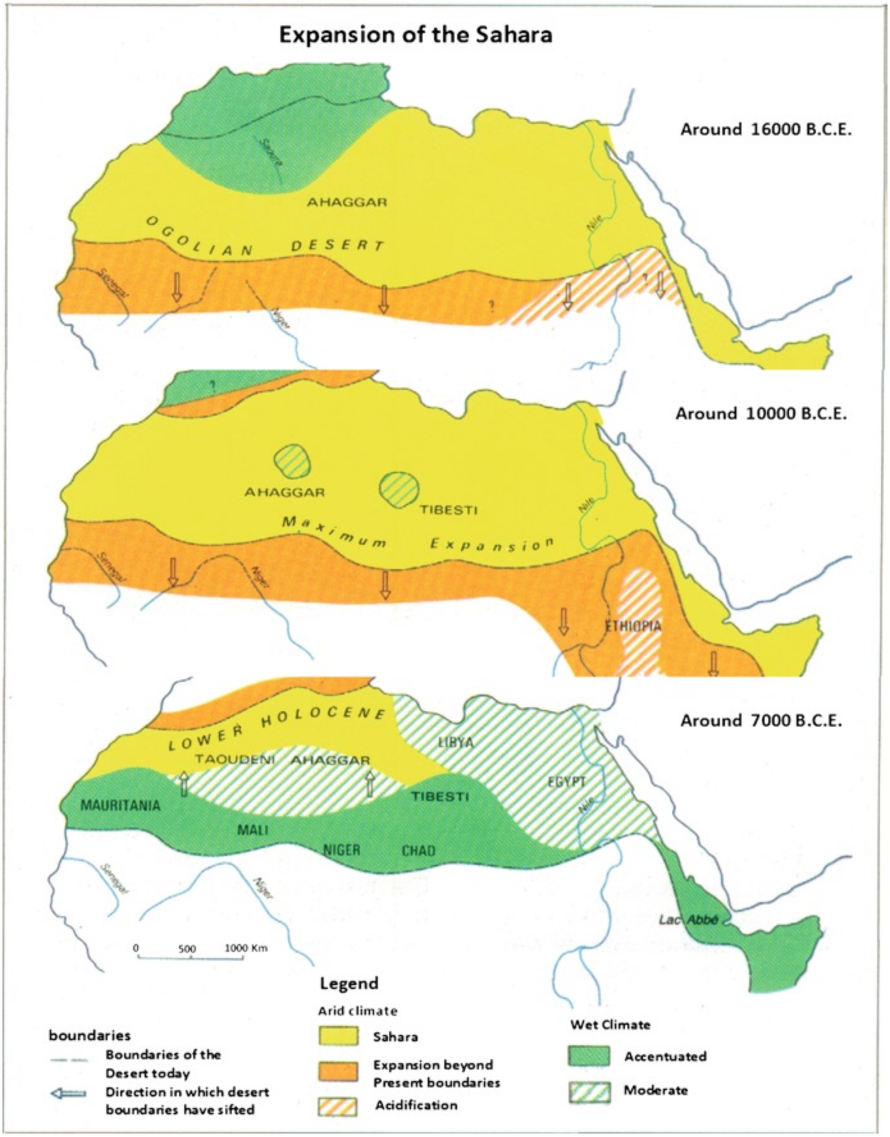

Fig. 29.6 The expansion of the Sahara around 16000 to 7000 BCE [2]

The human history associated with the River Nile—especially Pharaonic history—is part of the world's cultural heritage,. Climate controlled occupation in the Eastern Sahara during the main phases of the Holocene. Rainfall zones are delimited by best estimate isohyets on the basis of geological and archaeological data, as shown in Fig. 29.7. In part A of the figure, the abrupt arrival of monsoon rains in

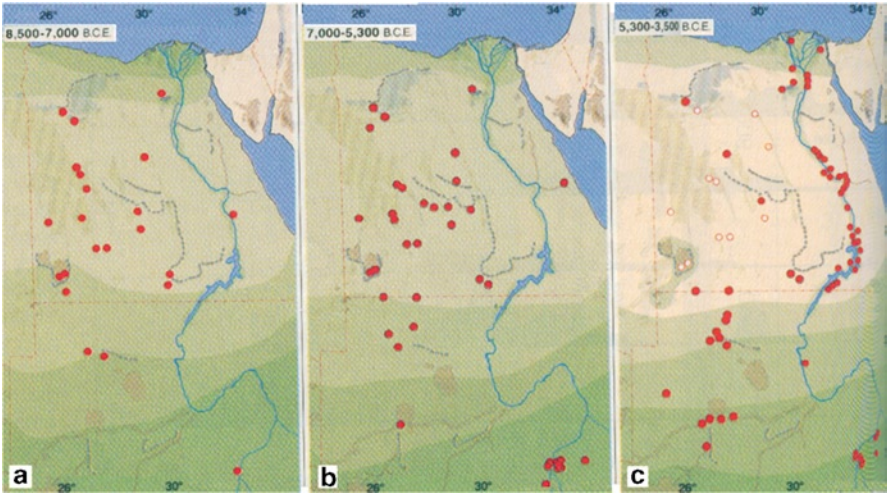

Fig. 29.7 Map of the archaeological sites in the western desert from 8500 to 700 BCE (**a**); 7500 to 5000 BCE (**b**); and 5300 to 3500 BCE (**c**). Red (*gray*) dots indicate major occupation areas and white dots indicate isolated settlements in ecological refuges and episodic human migration. The Saharan desert was devoid of settlements outside of the Nile Valley and extended about 400 km farther south than it does today [16]

8500 BCE is shown. Part B shows that after 7000 BCE, human settlements became well established all over the Eastern Sahara, fostering the development of cattle pastoralism. Part C shows that retreating monsoonal rains caused the onset of desiccation of the Egyptian Sahara in 5300 BCE, when prehistoric populations were forced to move to the Nile Valley as ecological refugees. The return of full desert conditions all over Egypt in 3500 BCE coincided with the initial stages of Pharaonic history in the Nile Valley [16].

With the pending climate changes that seem likely to prevail later in the twenty-first century, the countries of the Nile Basin need to be able to forecast the manifestations of these changes in the basin. The available global circulation models seem unable to make this forecast [13]. A regional circulation model, or a series of subregional models, each addressing one of the five climate systems prevalent within the Basin [14], needs to be developed. This would be a major undertaking that requires regionwide collaboration and substantial technical assistance.

29.4 National Needs

Due to the impact of climatic change on industry, agriculture, energy use and all other aspects of human life, a national research program in climate change is very important.

The general climate of Egypt is dry, hot, and desert-like. During winter, the climate of Lower Egypt (in the north) is mild with some rain showers, mainly over coastal areas. Upper Egypt is practically rainless with warm sunny days, but rather cool nights.

Data collected by Egypt Meteorological Authority and local universities for the period 1961–2000 have been analyzed and the following results were deduced [5]:

1. The mean atmospheric pressure has positive trend +0.026 hPa/year.
2. The mean maximum air temperature has positive trend of +0.34°C/decade.
3. The mean minimum air temperature has positive trend of +0.31°C/decade.
4. There is a positive trend in mean annual relative humidity of +0.18%/year.
5. There is a negative trend in sunshine duration of −0.01 h/year.
6. There is a negative trend in mean annual total radiation of −0.09 MJ/m^2.

These data indicate that there is a climate change trend associated with global warming. It is also concluded that there are increases in the number of hazy days, misty days, turbidity of the atmosphere, frequency of sandstorms and incidence of hot days (over 45°C). The frequencies of events of rising sand, sandstorm, haze, thunderstorm, and flash floods in Egypt are indicators of enhanced climatic variabilities. Extreme weather events in the last three decades have been studied from two points of view: frequency and severity. The number of days of maximum temperature equaling or exceeding 45°C increased in Upper Egypt from 50 days in the first decade to 52 in the second and reached 69 days in the last decade of the twentieth century. In the Western Desert, there were 37 extremely hot days in the last decade and only 22 days in each of the previous decades. The rest of Egypt did not experience an increase in the number of days with peak temperatures of 45°C or more. The Mediterranean coast of Egypt experienced successive increase in the amount of annual rainfall during the last three decades. The mean trend over the area is +0.76 mm/year [5]. The potential social and economic impacts of climate change would be serious for the country's future. The main key sectors relevant to climate change are: energy, transportation, industry, agriculture, and waste management. These activities produce greenhouse gas (GHG) emissions.

To mitigate climate change, Egypt needs to develop renewable source of energy, to use as fuel for industry and transport, domestic and industrial programs, energy-efficient buildings, and agriculture. Promotion of energy efficiency will develop environment-friendly energy and reduce GHG emissions. Further reductions of GHG emissions from the energy sector up to the year 2027 can be achieved through many actions. These actions as prioritized for Egypt's mid-term strategy include renewable energy, energy efficiency, lower-carbon fuels, nuclear power, and improved transportation fleets. In the area of mitigating industrial GHG emissions, the cement sector in Egypt is responsible for 17 million tons of CO_2 emissions per year, which is about 68% of the total GHG emissions of the industry sector. Egypt's Industrial Development Strategy issued in 2006 integrates climate change into national development priorities, and creates a market for climate- and environment-friendly technologies [3, 4].

The Nile Delta region is presently subject to changes, including shoreline changes due to erosion and accretion, subsidence, and sea level rise due to climate change. It is well known that the delta suffers from increasing land subsidence from west to east. Hence it is highly vulnerable to potential impacts of sea level rise. A national research program on climate change is very important now. This program may include exploring means for protecting the sea coasts against likely sea level rise.

29.5 Conclusions

From this paper, we can conclude the following:

1. Although solar activity during the last 30 years has declined to a deep minimum, global warming persists. Variations in solar activities do not seem to play a major role in determining present-day observed climate change. Prevalent global warming, caused by buildup of greenhouse gases in the atmosphere, seems to exceed and hence mask this solar effect, but it played a major role in paleoclimatic changes; for example, the climate cooling during the Maunder Minimum and Dalton Minimum was due to the collapse of solar activities.
2. To manage the water resources of the Nile Basin and to forecast possible changes to be associated with pending climate changes, we need to develop a regional circulation model, or a series of subregional models, each addressing one of the five climate systems prevalent within the Basin. This would be a major undertaking that requires regionwide collaboration and substantial technical assistance.
3. Locally, high impacts from climatic change are expected on industry, agriculture, energy use, and all other aspects of human life in Egypt. To mitigate climate change, Egypt needs to develop renewable sources of energy, to fuel industry and transport, domestic and industrial programs, energy-efficient buildings, and agriculture. A national research program on climate change is very important now. This program may include exploring means for protecting the sea coasts against likely sea level rise.

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Chapter 30
Adaptation Challenges for Water and Waste Management in the U.S. and China

R.H. Bowman Jr

Abstract Climate change poses huge challenges for the U.S. and China. Similarities between current environmental and economic conditions in China and past conditions in the U.S. suggest historic opportunities for investment. New paradigms are being developed to frame effective solutions.

30.1 Introduction

The background of the following is set while recognizing that in the granularity of the present challenges of water, climate change and the U.S. and China, we are forging new financial patterns that will define a post-neo-modern portfolio theory to benefit from.

I will capture some of the shock and awe that brought us to this point and convey the influence and confluence of factors that portend a historic investment opportunity in the U.S. and China.

The current economic pall only serves to slow down transitions underway in the global water and sewer industry and specifically those serving cities and those at risk due to climate change.

The ongoing deleveraging process is morphing and transferring the financial crisis to an economic crisis. It is the economic crisis response that with water in a realignment (consequence or partnership) there will be public and private solutions to urban water and sewer challenges.

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There is a capitalist lesson that will emerge from the challenges of water, cities, supply, demand and climate change. The most pronounced is the question of "is water a right or a service"?

All answers have geostationary relevance and geopolitical nuances but the questions and answers will foreshadow a county or region commitment to climate change, creation, storage, conservation, treatment, and disposal.

The eco question looming large over anyone's brand of global warming or climate change is: what is the relationship between the two economic superpowers, the U.S. and China? Is it cooperation or competition? I would argue it is *coopitition*. Both countries are competing for technologies but challenges of power, potable water, and sewage issues have become too big for government and both governments now know this. Having said that, they are cooperating in the unified front of carbon reduction and best practices where a competitive edge is not lost, and the private sector is mobilized to reap the benefits.

Global energy costs are at 2005–2006 levels. The economy dominates our thoughts and government and legislative animosity is at an all-time high. Good and knowledgeable environmentalists and change agents are in short supply. The emotional and organic 1970s environmentalist efforts are almost counterproductive to the bottom-line and below-the-line approach to solutions. By solutions I mean creation. Conservation is still the most target-rich and offers the swiftest return on investment, but creation of power, water, and sewage solutions for the urban port city is a business that requires financeable solutions with low risk and is the "Holy Grail." Along with the low risk of probable solutions and too few smart people, we need to rethink the process of thinking. If we rethink the process of thinking, then there is probably a solution. I am talking about applying new processes and technology to financial markets that are not up to speed with challenges or solutions. Most of our low-risk and legacy solutions are 30–60 years old. New technology solutions in the U.S. are almost impossible to finance and have legitimate scaling concerns. Venture capital is no longer venture, but production financing. When proof of concept is done and orders are placed—Wall Street appears to finance scale. Angel financing costs are an arm, leg, and a firstborn. In the U.S., we have old solutions for new problems in a very litigious environment. We often have the wrong tools in the toolbox and those tools are the wrong size. China is 61 years old with extraordinary change and growth and lacks the burden of the litigious world. They may have too many engineers in the same room disputing issues, causing similar delays to litigation, as is often the case (an unintended consequence of too many smart people). Financing solutions are easier at large scale, even for dated technology. In China as in the U.S., size gets eyes. The private sector is parachuting into China and making solutions work where government can't under the pall cloud of climate change.

Since 1946 it ranked 133rd of 146 countries assessed for environmental sustainability in 2005. Internal and external forces have changed China's view of environmental sustainability, contrary to many media outlets. Far from perfect and with much room for improvement, China is taking many appropriate actions and often because it can. China often calls on the private sector to execute on challenges that appear too big for government.

Similar to the U.S. with an economic and environmental lag of 30 years, China is at its low-water mark (pun intended). For the U.S., it was the spontaneous combustion (twice) of polluted waters in Ohio's Cuyahoga in 1969 that jump-started activism and then legislation. Our nation's rivers were convenient free sewers. Sound familiar? Enter the Clean Water Act of 1972, and 40 years later 16,000 sewage treatment plants are new or improved. Our collective stake in the ground, or the designation of the beginning of environmentalism, was with President Nixon and the formation of what is now the EPA. The various forms of the clear water and clear air acts took us from *monitoring* waste and pollution to *legislating* waste and pollution. The goal of the EPA in 1970 was to consolidate the federal government's numerous environmental regulations under the simple jurisdiction of a single agency. The EPA brought together 15 components from five executive departments.

Subsequent to new laws, we are using less water today than we did in 1980, but our population has gone up by more than 30 million people. In light of that Act, eight of our fastest-growing states are in drought conditions and 36 of our states will suffer water shortages over the next 10 years under normal circumstances; that is, absent the volatility of climate change. The reason for this is mostly that it is more costly to treat water or use less water than to meet new standards. We now export many manufacturing tasks or work to unburden our resources.

In China, during "The Great Leap Forward" of 1958–1961, the loss of 10% of the forests due to "Backyard Furnaces" to produce steel was catastrophic and led to flooding. Since the 1978 economic reforms in China, there has been a massive depletion of raw materials and mass production of goods. Of the more than 100 new environmental laws put in place since the 1970s, most have been ineffective until recently.

It should come as no surprise. Similar to the U.S. and since 1994, short-term economic gain in China has largely eclipsed enforcement of 30-year-old laws. In the U.S. and China it has been hard if not impossible to find evidence until recently for economic rewards (public or private) for reduction of power, water, or waste. Conversely, local governments and plant managers got rewarded for productivity. Follow the money!

Recently in China and due to natural resource protection, China now sets aside 15.1% of its footprint for reserves, which is far higher than the rest of the world. Set-asides are similar in the U.S. In Nevada, for instance, the federal government is the biggest landowner.

Inside China, 30-year-old activism protests in the U.S. are almost nostalgic today in China. In 2003, a Chinese consortium proposing 13 dams on the Nujang River was protested openly by nongovernmental organizations and students. It was thought that the dams would fill up and landslides would be deadly and the project was suspended.

In 2007 the construction at a $1.4 billion paraxylene plant in Xiamen City was protested for health reasons. The largest industrial project in that city was stopped.

Accordingly, China builds faster and cheaper because it can. China does not have as many eminent domain or right-of-way (ROW) issues due to the strong hand of the government. This is not a free land. The examples above show activism is alive and well in China. More recently in the U.S., during our election year, the environmental momentum and purpose—as they were—were frothy and emotionally charged. It was a historic environmental milestone which proved to be a chorus of "Coom by Ya," "We Are the World," and "I'm sick and tired and I'm not going to take it anymore." With $4.00 per gallon gasoline—the Toyota Prius car sales went from 6,000 per month to 25,000 over three (3) months—we were responding to the stick and not the carrot. In energy terms, in the 4 months of $4.00 a gallon gasoline, we consumed 80 billion gallons less year over year. This is not a pure data point due to the economy, but we got the point. If water and wastewater treatment were burdened like gas, we would use less or at minimum be more responsible. In Singapore they charge $3 a toilet per month to keep up with maintenance and technology changes.

It's over a year later and thank god some personalities have left center stage. Some people left kicking and screaming. Some people you couldn't get off TV. Overnight experts were preaching policy, legislation, and worse…solutions. People who have built nothing were advising people who have built nothing. Infotainment ruled the day and still does. "Science gate" has not helped the creation or distribution of good data. We still fumble over adjectives rather than data.

The "war on energy" or oil dependence on foreign supply has been a staple of every president since Nixon. What we have learned as Americans is that wars on nouns are unwinnable and lower the bar of expectations of government success. The war on drugs and terror really need no explanation here.

Global lessons of Kyoto have been lost. Crafted when "Biggie" and "PAC" were alive with a sentiment and intellectual capital of that era. It's old and concepts are dated. Up until the early to mid 1990s, the thing was that only anti-environmentalists could screw up Christmas. It's clear the pain of recognizing the difference between a developing and developed country is inconvenient, and so are the power and water and sewer challenges of the U.S. and China. The incumbent carbon burdens are a fur ball of socio and economic issues that has real pain. It's also clear that our leadership *then*, like our leadership *now,* does not want the burden of compliance to hit its collective balance sheet. Successful Kyoto will improve 1% of emissions with approximately $1 trillion of expense…and we didn't want to play. OK, got it! However, from a global perspective, climate change, global warming—or rather, high temperatures—will increase evaporation from the oceans and intensify the water cycle. Later this century there could be 8–10% more water vapor in the atmosphere or 800 million acre feet! That's 20 Nile Rivers with rain redistributed. The wet get wetter and the dry get dryer. Climate change is now responsible for not more but more stronger hurricanes. The *Journal of Climate* indicated that rising carbon levels could triple Category 5 hurricanes in the near future. The layperson can identify with projections in the U.S. and China with the frequency of 100-year storms! In defense of the poor meteorologists who get to shock and awe us into the foul weather frenzy as it comes, it only takes 10 years of data collection to establish a baseline for a 100-year storm. That's right, 10 years of data currently forecasts 100-year storms. Again, we need to rethink the way we think about these things!

Now post "Hopenhagen," or Copenhagen, as some refer to it, the elephant in the living room of life for the eco-economy is the U.S.' ambition vs. China's accountability. For productivity and greenhouse gas emissions. China was trapped and misled by the U.S. administration going into the conference. Expectations went south with little time to work out details and full intent. President Obama's "yes we can" mantra was drowned out as he flew out of an 8-h commitment to the summit with "Oh no he didn't"! We got China to commit to reductions that are expensive and hard to attain, in return for nothing! Let the mistrust begin!

New concentric circles of mistrust following this negotiation nightmare are:

1. China does not trust (expectations were set and unmet).
2. Copenhagen documents are watered down to "noted," not "adopted" by the international community. (An extraordinary, counterproductive conference where environmentally friendly hearts were broken.)

So with under 3 years remaining with an administration with a serious international environmental credibility issue, 18 months left on this sluggish economy (Great Recession), and money required for solutions, we are stuck with low or no expectations for the Cancun, Bonn, and Africa conferences. Ugh.

What we hope for is that discussions will not be left to the negotiators. We can hope for more smart people advising more smart people and we focus more on policy not politics.

The following frames the challenges and solutions. There are bright spots and plenty to feel good about. The shock and awe of "we are killing ourselves and the planet" indelibly inked in our collective minds in the 1970s needs to give way to hope, optimism, and change as is happening now in the U.S. and China. The pace is slow, but real.

About one-third of industrial wastewater and more than 90% of household sewage in China is released into rivers and lakes without being treated, but really this was the U.S. in 1972 and this is the point and recurring there to our collective challenges, planning, push back, and solutions. There are things we can do to treat incineration landfill, gasification, disposal at sea, and land application. All have consequences and climate change impact. China and developing countries need to recognize the consequences of at-all-costs productivity and apply technology, finance, and scientific solutions in a timely manner. Nearly 80% of China's cities (278 of them) have no sewage treatment facilities and few have plans to build any. Underground water supplies in 90% of cities are contaminated. China has 22% of the world's population, but only 8% of the world's fresh water. China has to be better at this than the U.S. Its economy depends on it. That fresh water is not strategically or even accidentally near the populated areas. In the U.S., 25% of the world's fresh water is in the Great Lakes. China and the U.S. have their mega cities on bodies of water for port access for industry. Less than 1% of the world's water is potable and it's that 1% that lubricates the world's economy. These are low-lying cities below sea level with inadequate fresh water. Climate change has our coast water creep between 1 and 3 ft with storm surge consequences of 10–60 ft depending on the tide, wind, and topology of the tide. The three lowest-lying major cities in the U.S. are NYC, New Orleans, and Miami. They are all at risk. Decentralized power or sewer solutions need to meet this growing demand.

Water shortages and water pollution in China are such a problem that the World Bank warns of "catastrophic consequences for future generations." Currently, China's population lacks safe drinking water, and nearly two-thirds of China's rural population—more than 500 million people—use water contaminated by human and industrial waste. By one estimate, one-sixth of China's population is threatened by seriously polluted water. One study found that eight of ten Chinese coastal cities discharge excessive amounts of sewage and pollutants into the sea, often near coastal resorts and sea farming areas. Just like Boston did up until the 1980s! Most of China's rural areas have no system in place to treat wastewater. China can boast the country with the most power from human excrement via the biogas investment. China authorities put in place 15.4 million systems in which organic materials ferment to gas in oxygen-free digesters. Which allow cooking stoves to operate hours later. In the U.S., one-third of our fresh water is exported via livestock and agriculture. 90% of U.S. waste is untreated as it meets fresh and salt water.

Water pollution—caused primarily by industrial waste, chemical fertilizers, and raw sewage—accounts for half of the $69 billion that the Chinese economy loses to pollution every year. About 11.7 million pounds of organic pollutants are emitted into Chinese waters very day, compared to 5.5 in the U.S., 3.4 in Japan, 2.3 in Germany, 3.2 in India, and 0.6 in South Africa.

Today water consumed by people in China and the U.S. contains dangerous levels of arsenic, fluorine, and sulfates. An estimated 980 million of China's 1.3 billion people drink water every day that is partly polluted. More than 600 million Chinese drink water contaminated with human or animal wastes and 20 million people drink well water contaminated with high levels of radiation. A large number of arsenic-tainted water supplies have been discovered. China's high rates of liver, stomach, and esophageal cancer have been linked to water pollution.

In many cases, factories fouling critical water sources are making goods consumed by people in the U.S. and Europe. Problems created by China's water pollution are not just confined to China either. Water pollution and garbage produced in China floats down its rivers to the sea and is carried by prevailing winds and currents to Japan and South Korea. The same in the U.S. The Colorado, Hudson, and Mississippi Rivers are not safe to swim in. with solid and human waste evident and in sight.

Water pollution and shortages are a more serious problem in northern China than southern China. The percentage of water considered unfit for human consumption is 45% in northern China, compared to 10% in southern China. Some 80% of the rivers in the northern province of Shanxi have been rated "unfit for human contact." This resembles 1970–1985 in the U.S. for the Jersey Shore, Boston Harbor, Hudson River, and a myriad of lakes.

A poll conducted by the Pew Research Center before the 2008 Olympics found that 68% of the Chinese interviewed said they were concerned about water pollution.

30.2 Effects of Water Pollution in China and the U.S.

I have swum around Manhattan twice. The smells and taste are not pleasant and unsafe; 14 waste facilities populate the perimeter. Recent improvements are noticeable and efforts are to be applauded, but more is needed. Canals are often covered by layers of floating trash, with the deposits particularly thick on the banks. Most of it is plastic containers in a variety of sun-bleached colors (Fig. 30.1).

Deformities in fish such as one or no eyes and misshapen skeletons and a decreasing numbers of rare wild Chinese sturgeons in the Yangtze have been blamed on a paint chemical widely used in Chinese industry. The same with fresh water for our 104 nuclear facilities in New York, Alabama, and North Carolina.

China is the largest polluter of the Pacific Ocean. The U.S. is the greatest polluter of the Atlantic Ocean. Offshore dead zones—oxygen-starved areas in the sea that are virtually devoid of life—are not only found in shallow water but also in deep water. They are mainly created by agricultural runoff—namely fertilizer—and reach their peak in the summer. In the spring, fresh water creates a barrier layer, cutting off the salt water below from the oxygen in the air. Warm water and fertilizers cause algae blooms. Dead algae sinks to the bottom and is decomposed by bacteria, depleting oxygen in deep water.

Nearly two-thirds of China's rural population—more than 500 million people—use water contaminated by human and industrial waste. Accordingly it is not all that surprising that gastrointestinal cancer is now the number-one killer in the countryside.

More than 130 residents of two villages in Guangxi Province in southern China were poisoned by arsenic-contaminated water. Arsenic showed up in their urine. The source is believed to be waste from a nearby metallurgy factory. Arsenic is the leading cause of well closures in New Jersey, where we close more than 15 wells per year.

Fig. 30.1 Waters that used to teem with fish and welcome swimmers now have film and foam at the top and give off bad smells

In August 2009, a thousand villagers gathered outside a government office in Zhentouu Township in Hunan Province to protests the presence of the Xiange Chemical factory, which villagers say has polluted water used to irrigate rice and vegetables and caused at least two deaths in the area.

Major polluters of the U.S. and China include chemical factories, drug manufacturers, fertilizer makers, power plants, paper mills, and computer chip makers.

In October 2009, Greenpeace identified five industrial facilities in southern China's Pearl River delta that were dumping poisonous metals and chemicals—such as beryllium, manganese, nonylphenol and tetrabromobisphenol—into water used by local residents for drinking. The group found the toxins in pipes that led from the facilities. This was also true in the Ohio River, the Great Lakes, and the Finger Lakes in the U.S. until the 1980s.

In February 2008, the Fuan textile factory, a multimillion dollar operation in Guangdong Province that produces enormous quantities of T-shirts and other clothes for export, was shut down for dumping waste from dyes into the Maozhou River and turning the water red. It turned out the factory produced 47,000 t of waste a day and could only process 20,000 t, with the rest being dumped into the river. It later quietly reopened in a new location.

Fig. 30.2 China has some of the world's worst water pollution

All of China's lakes and rivers are polluted to some degree. According to a Chinese government report, 70% of rivers, lakes, and waterways are seriously polluted, many so seriously they have no fish, and 78% of the water from China's rivers is not fit for human consumption. In a middle-class development near Nanjing called Straford, a polluted river was buried underground in a giant pipe while a new ornamental river, really a lake, has been built above it (Fig. 30.2).

According to one government survey, 436 of China's 532 rivers are polluted, with more than half of them too polluted to serve as sources of drinking water, and 13 of 15 sectors of China's seven largest rivers are seriously polluted. 30 years ago this was the same in the U.S. The most polluted rivers are in the east and south around the major population centers with the pollution getting worse the further downstream one goes. In some cases each city along a river dumps pollutants outside their city limits, creating increasingly more pollution for the cities downstream. As it relates to greenhouse gas, the World Commission on Dams warned that in addition to obvious and chronic pollution in our rivers and reservoirs, greenhouse gases produce one-fifth the manmade methane and 7% of greenhouse gases. That's more than aircraft. Due to organic rotting, our storage capacity in U.S. is diminishing by 1% per year; China, which has more reservoirs and dams than anyone, is losing 2%. The world requires 300–400 dams just to keep up with demand and to make things worse, in the past 50 years 322 dams have failed due to poor maintenance and decay.

Many rivers in the U.S. and China are filled with garbage, heavy metals, and factory chemicals. Natural containments plague the solutions as well. Although the West deploys lawyers rather than engineers to solve most of its problems—the headwaters of the Colorado contain about 50 ppm of salt. By the time the water gets to Las Vegas and the last dam it contains more than 700 ppm. Crop loss due to salt in the U.S. is estimated at $330 million annually. Suzhou Creek in Shanghai stinks of human waste and effluence from pig farms. There have been devastating fish kills caused by the release of chemicals into the Haozhongou River in Anhui province and Min Jiang River in Sichuan Province.

The Huai flows through densely populated farmland between the Yellow and Yangtze Rivers. Bottlenecks and elevation changes make the river both prone to flooding and collecting pollutants. Half the checkpoints along the Huai River in central and eastern China revealed pollution levels of Grade 5 or worse, with pollutants detected in groundwater 300 m below the river. Across the poor developing and developed countries of the world, one-tenth of the world's irrigated crops (e.g., rice, wheat, lettuce, tomatoes, mangos) are watered by smelly, clumpy sewage that is untreated out of sewage pipes.

The Huai river in Anhui province is so polluted all the fish have died and people have to drink bottled water to avoid getting sick. Some places have water that is too toxic to touch and leaves behind scum when it is boiled. Here, crops have been destroyed by irrigation water from the river; fish farms have been wiped out; and fishermen have lost their livelihoods. The South-North Water Transfer Project—which will travel through the Huai basin—is likely to deliver water that is dangerously polluted.

Half of China's 20,000 petrochemical factories lie on its banks. About 40% of all wastewater produced in China—about 25 billion tons—flows into the Yangtze, of which only about 20% is treated beforehand (Fig. 30.3).

The pollution has taken its toll on aquatic life. Fish catches from the river declined from 427,000 t in the 1950s to 100,000 t in the 1990s. The Yangtze is in danger of becoming a dead river, unable to sustain marine life or providing drinking water.

Fig. 30.3 The Yangtze River is polluted with 40 million tons of industrial and sewage waste

Fig. 30.4 Dead fish in Hangzhou pond

According to report by the Chinese Academy of Sciences released in April 2007, the Yangtze is seriously and largely irreversibly polluted. More than 600 km of its length and almost 30% of its major tributaries are in critical condition.

Sections of the Grand Canal that have water deep enough to accommodate boats are often filled with trash sewage and oil slicks. Chemical waste and fertilizer and pesticide runoff empties into the canal. The water is mostly brownish green. People who drink it often get diarrhea and break out in rashes (Fig. 30.4).

Studies have shown that the quality of coastal waters is deteriorating quickly as a result of land-based pollution. The study found that 8.3 billion tons of sewage was released in Guangdong Province's coastal waters in 2006, 60% more than 5 years earlier. All together, 12.6 million tons of polluted material was dumped in waters off the southern province.

30.3 Efforts to Combat Water Pollution in China and the U.S.

Alarmed by the amount of pollution in its rivers, China has begun enacting new environmental regulations and laws and taking more action to clean up its rivers. Beijing is closing polluting factories, building new sewage treatment plants, and changing agricultural practices. To clean up Suzhou Creek in Shanghai, government officials are moving polluting factories and sewage is being diverted to the Yangtze River, which flushes out to the sea. Elsewhere, local officials have rejected plans to build metal-plating factories over concerns about pollution (Fig. 30.5).

In August 2006, the Chinese government admitted that China has serious water pollution and drinking water problems and earmarked $132 billion for cleaning up and improving China's water supply. Allocations included $30 billion for urban water supply projects and $50 million in wastewater projects. Projects include sewage works, pipes, desalination plants, and the South-North Water Diversion Program. Environmentalists estimate that for China to truly address its water problems, it needs to spend $300 billion on antipollution equipment alone.

China wants to reduce water pollution discharges by 10% between 2008 and 2010. More than $8 billion was spent on cleaning up the Huai River basin in Henan and Anhui Province in the 1980s and 1990s. Great progress was made. In the mid 1990s the cleanup was heralded as a great success and much of the work stopped. By the mid-2000s the river was polluted again; in many cases worse than it was before.

Fig. 30.5 Water treatment plant

Laws on the books are widely ignored. There is little transparency. Money earmarked for wastewater projects is sometimes re-appropriated to build power plants. Local officials have close relationships with business owners that own the factories and mines that cause the pollution.

In some cases the local governments that are supposed to do something about pollution are the same ones that own the factories that do the polluting. That is the case with a huge MSG factory In Xiangcheng in Henan Province that employs 8,000 people and produces toxins like ammonia nitrate. One official who spoke anonymously to the *New York Times* said of the government in Xiangcheng: “There are a lot of officials who don’t care about pollution. Some leaders are just interested in making money” [2].

Sometimes there are protests. In July 2007, police clashed with thousands of people in Yuanshi, a town in Sichuan Province, angry over pollution of local water supplies by a brewery. Seven villagers were detained and 20 were injured. The protest began after the brewery dumped wastewater that contaminated drinking and irrigation water.

Are challenges of water population and water management too big for government? Many Chinese cities have outsourced their water treatment to large private companies. The French company Veolia alone manages water systems in 17 Chinese cities, including Changzhou, Lizhou, and Shanghai. The water situation in these cities has been dramatically improved but residents now have to pay a significant amount of money for water that in the past was free or nearly free [3].

In Shanghai, where Veolia has a $243 million, 50-year contract, the French company has laid 900 miles of large-diameter pipes, hooked up 300,000 new structures to the water system, built sewage and water treatment plants, and hired 7,000 local people between 2002 and 2006. To pay for all this, Veolia is gradually raising water prices.

Some pensioners in Lizhou pay a quarter of their $40 a month pension for water. When asked about conserving water, one pensioner said he lived in a building with 70 or so apartments and his water bill was determined by dividing the total bill among building residents, meaning that one person's effort to conserve water would bring few rewards if others wasted water.

Long Cun is a large village on the Liu River in Guanxi Province that is down river from a paper mill that dumped so much pollutants into the water the river became "as black as soy sauce." Villagers complained and have been given piped water from the city of Lizhou. The only problem is that the residents of the town have to pay $4 a month for their water, a considerable sum for people who only earn $20–$30 a month.

Paper mills in the U.S. have same challenges. They take up landfill but water treatment laws from the 1980s have water treated and contained.

Solutions for the U.S. and China are now becoming abundant. Scaling new technology and making it financeable is the first challenge for both the U.S. and China. Legacy technology that we dummy down to and for the investment community need to be brought swiftly to the market and scaled. The support of past sector finance is timely and appropriate, but the windows of timeliness to design and permit appear to be crafted by overenthusiastic negotiators rather than builders. Approximately 75% of incentive money from TARP and ARRA are not committed to, with 5 months to go before expiration! Will we shovel the funds out the door to save face or extend the programs? Time will tell. Money and real estate continue to slow the wheels of true progress in the U.S. Money, scale, and real estate or where to put solutions on urban port cities will continue to slow progress. China has a greater advantage in addressing that challenge. The strong hand of government is helpful. Technology and science have benefitted the chorus conundrum of carbon, pollution, money, and real estate for the urban environment.

We are partners in these challenges with healthy competition for doing better in a form of nationalism.

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Chapter 31
Adaptation to Climate Change and Other Emergent Conditions with Inland and Terrestrial Infrastructure Systems with Application Case Studies

J.H. Lambert, C.W. Karvetski, and I. Linkov

Abstract This paper describes several cases that explore the impacts of potential emergent conditions, including climate change and other factors, to infrastructure systems and mission assurance. The cases suggest a need to account in strategic planning for combinations of emergent conditions, including climate, economic, technological, social, and political conditions. We define scenarios to be specific combinations of diverse emergent conditions. We discuss the implications of emergent conditions for multicriteria analysis of strategic investments. The identification of influential emergent conditions can focus investigative and modeling efforts on issues of concern for long time horizons. The several cases are: (i) inland training ranges in Alaska, (ii) communities of Alaska vulnerable to coastal erosion, and (iii) energy security of military installations. The approach is generalizable to highlight the combinations of emergent conditions that should be influential to adaptation and strategic planning for inland and terrestrial infrastructure systems.

31.1 Introduction

Climate change influences sea levels, ocean acidification, severity and frequency of extreme weather, the balance of ecosystems, and other phenomena of importance to natural and manmade systems [10, 16, 23, 34, 78]. Climate change has serious implications for long-term national security [1]. During the past 50 years, relative

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sea level rise has been estimated to be 8 in. in some coastal areas of the U.S., and recent research from the U.S. Global Change Research Program has expanded on the fourth report from the Intergovernmental Panel on Climate Change and increased the estimates of relative sea level rise over the coming century [23, 78].

Uncertainties about climate change and sea level rise can be addressed through scenario analysis [57, 78]. Future societal response to climate change and various degrees of sea level rise is unclear, and ultimately affects the impact of response policies and investments [5, 54, 58, 59, 66]. Growing population and present and future coastward migration could increase the need for coastal protection [58, 59]. Ongoing development and the increase in and aging of coastal infrastructure systems increase the consequences and risks of climate change and sea level rise. Multicriteria and other decision analysis tools are frequently used to perform risk and impact analysis on environmental and infrastructure systems [42–45]. There are several assessment tools for decision makers to evaluate adaptive and protective measures for the possibilities of climate change [54]. Previous efforts have combined scenario planning and multicriteria decision making [29, 52]. A challenge is how best to aggregate the contentious and morphing preferences of multiple stakeholders and decision makers for climate change [68]. Often the approach needs to be able to incorporate partial information [48]. For modeling decisions related to climate change, Keeney and McDaniels [31] have advocated a value-focused thinking approach [30].

The U.S. Army Corps of Engineers (USACE) is concerned with incorporating the direct and indirect physical effects of projected sea level rise in the management, planning, engineering, design, construction, operation, and maintenance of USACE projects and systems of projects [22, 76, 77]. USACE recommends using multiple rates of sea level rise scenarios to address uncertainty while evaluating project alternatives. Evaluating and designing alternatives over the full spectrum of sea level rise rates should increase the chance of selecting the appropriate projects for success [35]. Analyses must consider the issues of human health and safety, economic costs and benefits, aging infrastructure systems, environmental and ecological aspects, and other social effects [76, 78]. The Engineer Research and Development Center (ERDC) of USACE held a workshop in August 2009 to obtain and focus knowledge and insights concerning USACE environmental and risk assessment and risk management issues, priorities, and key activities related to climate change. Participants expressed need for decision methodologies for prioritizing project alternatives for climate change and sea level rise that can incorporate multiple stakeholders and decision makers as well as provide insight when only partial information is available. Decision methodologies that can handle scenario uncertainties would enable timely action for potential climate change and sea level rise.

Recent efforts have used decision analysis to find the extent to which the scenarios present threats and opportunities to the Department of Defense (DoD) and other missions in several areas: (a) Afghanistan infrastructure development with emergent conditions, (b) energy security of installations, (c) coastal erosion in Alaska, and (d) long-range multimodal transportation planning. Each of our efforts to date has been "high-risk/high reward" in that a modest effort in principled, multidisciplinary expert elicitation and multi-objective planning has been able to identify non-obvious influences of critical scenarios that are combinations of multiple phenomena. Our Afghanistan effort had identified a portfolio combination of natural disasters and refugee migration on the Pakistan border, even as an earthquake occurred in the key border province of Nangarhar in 2009 [29]. An effort addressing energy security considered portfolios of regulatory and economic stressors to be foremost in affecting energy security of DoD installations (presented at the 2009 meeting of the Society for Risk Analysis [28]). The Alaska effort on coastal erosion focused our capabilities to investigate climate change and its many manifestations in portfolios of salinization, storm frequencies, and sea level rise as we explored coastal communities of particular concern for erosion. A related effort with long-range planning for multimodal transportation systems has provided experience in integrating forecasts and planning assumptions from multiple science and engineering and public policy disciplines [36].

31.2 Case of Alaska Inland Military Training Ranges on Permafrost and Tundra

The Secretary of the Army and the Chief of Staff of the U.S. Army have described the need for the Army to transform to meet the current and emergent demands for the twenty-first century [75]. Alaska is an integral component in the achievement of relevant missions and training for the U.S. Army. After balancing multiple stationing, training, system acquisition, and deployment objectives with biological, physical, and socioeconomic objectives, a decision alternative (Alternative 4 [75]) was made to transform the 172nd Infantry Brigade into a Stryker Brigade Combat Team (SBCT). This alternative includes additional personnel within U.S. Army Alaska (USARAK) and new training practices, among other requirements.

There are considerable anthropogenic stressors (some related to climate change) that present both threats and opportunities for U.S. military operations and inland ecological systems of Alaska. Such stressors include direct effects of temperature change on atmospheric and hydrological processes, alterations in the frequencies of extreme storms and droughts, changes in wildfire activity, alterations of animal and plant ecology (e.g., invasive species, forest pests, animal migrations, diseases), and changes in human population, industrial development, resource management, and associated socioeconomic issues. Particular stressors for DoD missions relevant to this effort are the changes to the permafrost regime (melting and ground stability being a large concern), increased vulnerability of forests to wildfires, and direct effects of climate change on the boreal forest structure and functioning.

When the influence of a single stressor is beginning to be understood, the influence of multiple stressors combined in a portfolio introduces significant challenges to modeling of potential regime shifts of ecological systems. Such understanding is urgent in Alaska, where policies and large investments in the science and protection of ecological systems by the DoD and others are ongoing to mitigate the effects of climate change on lands that the Army, Air Force, and others use as training ranges. For example, an important consideration for the transformation plan and also for training and mission activities at Fort Wainwright and Fort Richardson includes Alaskan wildfires. While wildfires are an important process for the functionality and productivity of Alaskan ecosystems, they certainly impose risks to infrastructure, human systems, and Army training practices and missions. The Alaska Wildland Fire Management Plan allows for the establishment of fire management options according to land use objectives and constraints [75]. There are four management options provided for land managers, ranging from a Critical Management Option to a Limited Management Option.

The vulnerability of training grounds to fire-induced threats is a function of many dynamic variables. Specifically, climate factors, human activities, and vegetation all affect this vulnerability. Different weather events and trends can increase the potential for new fires and different tree species present different risks for the initiation and fueling of forest fires. Different military activities require different munitions and pyrotechnics. Alternative 4 [75] requires an 82% increase in munitions. From 1980 through 2000, 148 wildfires were reported on Fort Wainwright [75]. Most of these forest fires (117 out of 148) were attributed to human causes, including 85 that were due to military operations [74]. Different burn plans are considered for different areas of Fort Wainwright, with each plan focused on different objectives. New shifts in training activities due to the transformation plan will likely affect the probabilities and consequences of different fire scenarios. Likewise, changing climate conditions could influence the availability of training grounds throughout the year. With different assumptions for future climate change, coupled with different assumptions of ecosystem dynamics, there could be an increase in the vulnerability of critical training and missions to Alaskan wildfires.

Permafrost warming has been observed for numerous sites throughout inland Alaska over the last several decades [11], which could lead to permafrost melting and ground instability, affecting both ecological systems and the availability of land for different vehicles and weapon systems. In particular, the maneuverability of newly acquired Stryker vehicles could be lessened or restricted seasonally in future years. Nevertheless, Alternative 4 [75] also requires maneuver space and maneuver impact miles (MIMS) to increase by 410%. From an ecology perspective, climate change effects on ecosystems will create significant challenges for DoD natural resources managers who follow guidelines prescribed in installation-specific Integrated Natural Resources Management Plans (INRMPs). Alaskan military installations currently support a high level of floral and faunal diversity. As landscapes change due to stressors, and species' ranges expand and contract, it may become increasingly difficult to maintain this diversity at the installation level (and create potential regulatory challenges to deal with changes in federal status of species). For example, changes in wetlands resulting from increased evaporation (decrease in wetlands) or permafrost thawing (net wetland expansion) could result in net losses or gains of important breeding habitat for globally important populations of migratory waterfowl and shorebirds. Migratory birds are of particular DoD management interest because of the DoD's responsibilities as a federal agency under the Migratory Bird Treaty Act and Executive Order 13186. More than 20 species of migratory non-game birds occur on Alaska DoD installations that have been identified as species of concern by the U.S. Fish and Wildlife Service, Office of Migratory Bird Management, the State of Alaska, or Boreal Partners in Flight Working Group because of declines in populations. Changes in net acreages of wetlands coupled with the need to use lands for testing and training may also create significant regulatory compliance issues for DoD. Certain combinations of climate scenarios and mission scenarios could create a "perfect storm" for severely crippling mission and training execution and success for DoD [1].

Alaska provides over one million acres of land for the DoD to accomplish various land- and air-based testing and training missions. Potential environmental and other changes are likely to alter a significant portion of this landbase and potentially impact DoD missions. Climate change in Arctic regions is already having significant impacts to Alaska ecosystems that are likely to increase under anticipated future conditions. Altered weather patterns are expected to significantly affect Alaskan inland ecosystems, with environmental consequences such as degradation of permafrost, changes in the fire regime, alterations of insect outbreaks, and changes to availability of habitat for sensitive species. There is in addition considerable diversity and intensity of other anthropogenic and non-anthropogenic stressors that could present both threats and opportunities to military operations adjacent to the inland ecological systems of Alaska. We outline here the need for a multidisciplinary investigation of Alaska climate change scenarios, ecological assessments, and DoD management alternatives to understand how adjusting the seasonality of military operations and controlled burns will yield the greatest benefits for the vast acreages of military lands in Alaska and the surrounding ecosystems. State-of-the-art predictive modeling that couples climate change information with potential landscape-scale alterations to training land will provide DoD with the necessary information to assist decisions on how to: (i) shift or alter training and other operations, and (ii) select appropriate environmental management alternatives to mitigate the consequence of climate change on the mission. The proposed effort is unique in identifying and prioritizing the key stressors among climate, environment, mission, regulatory, security, technology, and other stressors to be addressed in a comprehensive decision analytical framework.

Uncertainties about climate change and other anthropogenic and non-anthropogenic emergent conditions and stressors will be addressed, individually and in combination, through a scenario-focused analysis [23, 78]. The ecological impacts of climate change in its various forms are unclear, and ultimately affect response policies and investments. Multicriteria and other decision analysis tools will be adapted to perform risk and impact analysis on environmental and military systems [18–21, 42, 44, 45, 84, 85]. Evaluation of adaptive and protective measures for the possibilities of climate change will benefit from previous efforts. These efforts have combined scenario planning and multicriteria decision making [29, 52]. The approach will make significant progress to integrate results of multiple science disciplines, stakeholders, and decision makers for climate change. The approach can be tailored as necessary to incorporate partial information [63]. The work of Keeney and McDaniels [31] and Keeney [30] addressing climate change will be adopted in part.

Climate modelers use three downscaling approaches: regional climate modeling [46], time-slice simulations with a higher-resolution model driven by a global climate model [7], and statistical downscaling [80]. Regional models are computationally prohibitive while statistically downscaled data is limited to fields that are observed at meteorological stations. So the type of downscaling method used must be tailored for the problem under investigation. For this research, we propose to use a combination of dynamically and statistically downscaled climate data over interior Alaska to provide a range of possible future conditions for ecosystem impacts. For the climate-model downscaling, we will employ the National Center for Atmospheric Research (NCAR) Community Climate System Model Version 3 (CCSM3) for the global scale (A1B scenario) and a sophisticated Arctic regional modeling system, the Arctic MM5, for the high-resolution simulations. Dynamically downscaled data is available for 1979–1999, 2010–2019, 2050–2059, and 2090–2099 for the middle-of-the-road A1B scenario. These data are available at a 25-km and 10-minute resolution over Alaska. The full range of dynamical variables is available for analysis (e.g., temperatures, winds, evapotranspiration, and humidity at all levels in the atmosphere). Dynamical downscaling and bias correction methodology is provided in Zhang et al. [82, 83].

Statistically downscaled temperature and precipitation data are available from the SNAP, the Scenarios Network for Alaska Planning (www.snap.uaf.edu). SNAP has downscaled five models that best represent Alaska climate for three emission scenarios (A2, A1B, and B2) over the period 1980–2099. A1B is the midrange scenario, A2 is more pessimistic, and B1 represents lower emissions. Statistical downscaling provides a continuous time series but for fewer variables. Additional meteorological variables that are required for understanding impacts to ecosystems will be statistically downscaled from the IPCC models using observed meteorological information at stations. This will provide the relevant future scenario information at the locations of stations. The following are the elements of the approach:

- Key emergent conditions. Refining a selection of (i) anthropogenic and non-anthropogenic emergent conditions and stressors, (ii) alternative actions and policies, focusing on controlled burns and adjusting seasonal use of the training lands for various activities, and (iii) training- and mission-relevant performance criteria.
- Climate-model downscaling and data collection. Identifying and collecting relevant results of climate models that are amenable to downscaling. Identify and collect historical data and records of wildfires and permafrost conditions, as well as projected wildfire and permafrost scenarios with climate change, including causes and consequences with regard to environmental conditions.

- Environmental and ecosystem modeling. Describing potential impacts of landscape alterations by projected wildfire and permafrost scenarios on species and ecological communities and the implications for DoD environmental and regulatory compliance.
- Systems analysis and integration. Integrating these components within a systems analysis of potential regime shifts of Alaska ecological systems, with multicriteria decision methodology extended by a scenario-focused approach that has been used by the authors for Afghanistan, Alaska coastal erosion, and energy security.
- Validation and testing. Validating the approach on one or more installations comprising the 1.5 million acres of Alaska military reservation, while collecting and integrating expert knowledge from multiple science disciplines.
- Implementable alternatives. Prioritizing the variety of control options, focusing on seasonality of operations and controlled burning, and identifying the most influential combinations of actions and scenarios in terms of mission benefits and vulnerabilities of ecological systems in Alaska. Ensure that the analysis of alternatives can distinguish the impacts of climate change from the impacts of other anthropogenic and non-anthropogenic drivers.

Progress in the above elements can focus resource-intensive and costly investigations to the factors most affecting ecological systems of Alaska. The plan integrates principles and results of multicriteria decision analysis, climate modeling, permafrost modeling, and DoD environmental analyses to characterize the potential impacts to inland Alaskan ecological systems of diverse scenarios of climate change, focusing on changes in wildfire regimes and permafrost dynamics. The integrated contribution of the above activities is a capability for multiple agencies (military and others) to identify and manage the ecosystem impacts of a range of environmental change scenarios that bridge multiple science and engineering disciplines. The capability to be provided by this effort is crucial for addressing the sustainability of ecological systems and military operations on all inland military lands in Alaska. We can identify and prioritize among the diverse environmental stressors for ecological protection of upland tundra and forest systems related to military missions in Alaska. We can apply established principles of multicriteria decision analysis and scenario-focused planning with science and engineering expertise for identifying potential regime shifts in the ecological systems. We can incorporate expertise and modeling contributions from multiple disciplines focusing on how combinations of stressors affect the value parameters within a multicriteria decision analysis for DoD actions affecting the health of ecological systems. The results of our analysis of emergent conditions including climate change will help to focus multidisciplinary investigations. The investigations identify the greatest payoffs for the U.S. military and Alaskan ecological systems, particularly identifying the impacts of various combinations of emergent conditions, including climate change stressors and potential regime shifts.

31.3 Case of Alaska Inland Communities Vulnerable to Erosion and Climate Change

Ongoing efforts in Alaska are addressing risk to water resources projects related to climate change. There is a significant need to address flood risk management, storm damage reduction, and erosion prevention. Climate change has the potential to impose severe stress on coastal environments and local inhabitants [56]. Alaskan coastal communities have witnessed erosion and other changes in environment that have led to significant damage to infrastructure, human health and safety, and economic prosperity. Over the past century, the mean annual temperature in Alaska increased by 1.4°C compared to the global average of 0.8°C [79]. These stressors threaten to impact the livelihood and social dimensions of Alaska communities. Our approach aims to identify the range of consequences of multiple scenario assumptions of climate change on the targeted communities. This effort has developed an interactive software tool to be used in assessing the relative importance of potential scenarios as well as the influence of these scenarios on the communities. This approach should be interest to engineers, policy makers, scientists, and stakeholders concerned with coastal erosion in Alaska and cold regions around the world. The approach is applicable for communities and projects outside the scope of Alaska and environmental change.

Climate change can manifest as sea levels, ocean acidification, extreme weather, ecosystem balance, and other phenomena of importance to natural and manmade systems, as well as long-term national security issues. Climate and other uncertainties should be addressed through scenario analysis when considering societal issues and response policies and investments. The consequences and risks of climate change and sea level rise are increased by ongoing development and the aging of coastal infrastructure protection. USACE is concerned with incorporating the direct and indirect physical effects of projected changes of climate to the management, planning, engineering, design, construction, operation, and maintenance of USACE projects that mitigate coastal erosion. Multiple rates and events of climate change address uncertainty in the evaluation of project alternatives. Evaluating and designing alternatives over the full spectrum of sea level rise rates and other scenarios increases the chance of selecting the appropriate projects for success. Such analyses must consider the issues of human health and safety, economic costs and benefits, aging infrastructure systems, environmental and ecological aspects, and other social effects. Our effort in this case study is identifying the most influential scenarios for infrastructure policies and investments for protection from coastal erosion. The methodology quantifies the sensitivity of 26 Alaska communities to a variety of scenarios. Figure 31.1 is a map of the communities within Alaska that are known as Priority Action Communities for erosion prevention [77].

The general approach to study scenarios of emergent conditions, including climate change, is as follows. For each of several climate change and other scenarios of emergent conditions, the approach elicits from experts the increases or decreases in importance of criteria to rank the communities for erosion concern. With assessments of

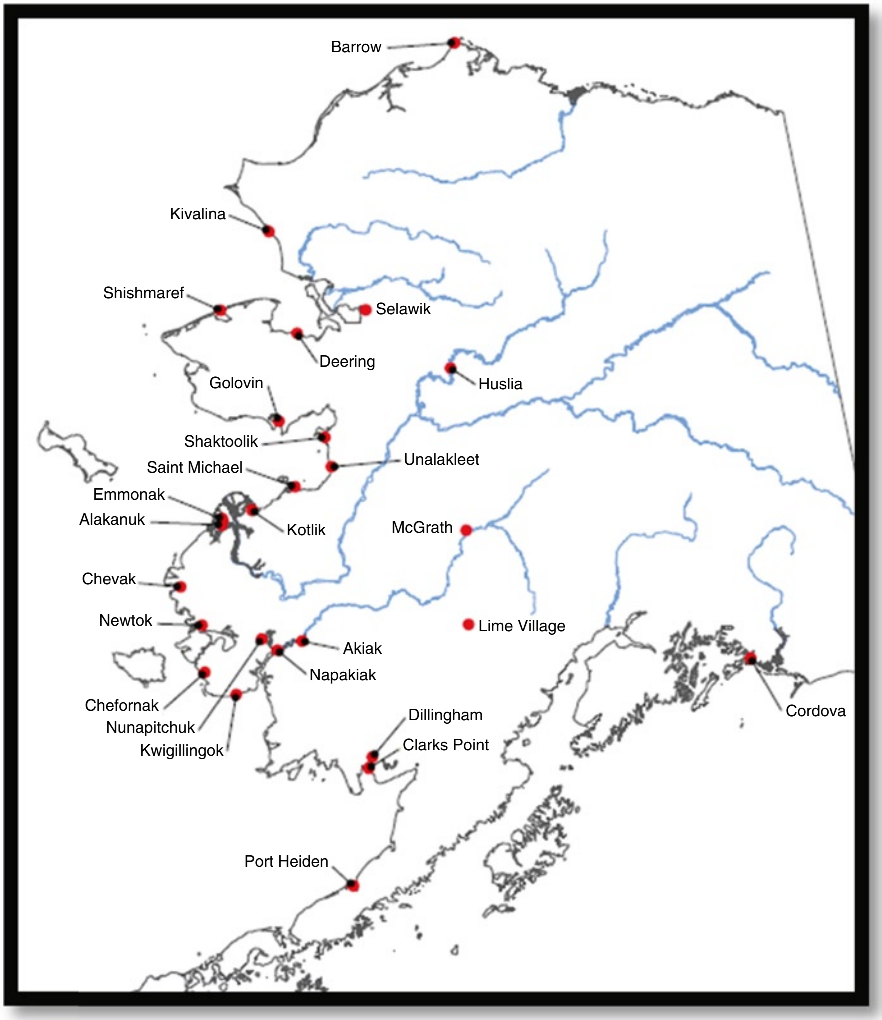

Fig. 31.1 Priority Action Communities in Alaska [77], which are identified as having the highest level of erosion concern

each community across the criteria, the approach can study the sensitivity of community rankings to the scenarios. The set of criteria used for rating the communities is provided in Table 31.1.

Nine criteria are adapted from the USACE Baseline Erosion Assessment [77]. The criteria are assigned baseline relevance that reflects the degree of importance of each criterion relative to the others, not yet considering climate change scenarios. The user is given the opportunity to adjust these values in accordance with current project conditions and stakeholder values. For each criterion there are four relevance

Table 31.1 Criteria for erosion protection. Nine criteria used in assessment of erosion potential of Alaska communities [77]

Critical infrastructure
Human health and safety
Subsistence and shoreline use being limited
Community settings/geographic location
Housing and population
Housing in parallel
Environmental hazard
Cultural importance
Commercial/non-residential

ratings (No Relevance, Low Relevance, Medium Relevance, High Relevance). The impact ratings for the communities on the criteria are High Impact, Medium Impact, and Low/No Impact. The erosion-severity score is calculated for each project using an additive value function derived from the ratings and criteria weighting. For a given project, the rating for each criterion is multiplied by the weight received by each criterion. These numbers are summed together for all criteria to yield a baseline damage score. This score identifies how responsive each project is to the relevant criteria compared to the other projects. The important consideration is how the value of any one damage score ranks among the other scores [77]. The innovation of this approach is to consider how project damage scores are impacted by different scenarios, thus altering the ranking of needs. Once damage scores are calculated for each project, the user has the opportunity to define up to 16 scenarios based upon a subset of up to 26 conditions. These conditions comprise various environmental, social, and commercial factors. These represent potentially realizable conditions that can have an impact on at-risk communities. Conditions include sea level rise, decrease in sea ice, loss of species, increase in human population, and decreased tourism. The user can then define scenarios to be any combination of the conditions. Though default scenarios are provided, these scenarios may be defined specifically to the projects at hand. For each scenario, the user can specify how each criterion shifts in importance should that scenario occur. The assessments available include: No Change in importance; Large Increase; Small Increase; Small Decrease; and Large Decrease. These options are assigned parameter values to reflect the degree to which the criteria are adjusted. The user then evaluates each criterion to reflect which of the five options best describes the new relevance based on the presence of a scenario. The adjustments create unique weightings for the criteria under each scenario derived from the weightings for the criteria under the baseline. These new weightings are then applied to the user's previous assessment of each project's impact. A new damage score is calculated for the projects over each scenario, based on these new weightings. The output data resulting from this calculation is housed in a table and can be represented visually using graphs depicting sensitivity of rankings to scenario assumptions. This new data can be analyzed to (1) determine adjusted prioritization for communities under each scenario and (2) elicit information to identify the most impactful scenarios. Figure 31.2 describes scenarios of

Scenarios

	Baseline	Sea level rise > 1m	Decrease in sea ice	Storm surge + Increased erosion	Sea level rise < 1m	Increase in sea ice	Increased Flooding	Decreased
Conditions	S00	S01	S02	S03	S04	S05	S06	S07
Sea level rise < 1m					☑			
Sea level rise > 1m		☑						
Increase in sea ice						☑		
Decrease in sea ice			☑					
Increase in wave height								
Storm surges				☑				
Increased erosion				☑				
Decreased erosion								☑
Increased flooding							☑	
Decreased flooding					☑			
Permafrost melt		☑						
Wild fires								
Drought								
Increase in soil salinity								
Decrease in soil salinity								
Loss of species								
Loss of habitats								
Increase in storm frequency								
Decrease in storm frequency								
Contamination of water supply								
Increase in human population								
Decrease in human population								
Increased tourism								
Decreased tourism								
Increased industry								
Decreased industry								

Fig. 31.2 Definition of scenarios composed of emergent conditions of climate change and other factors

emergent conditions in assessing erosion potential of Alaska coastline communities. The scenarios represent combinations of emergent conditions that are suggested from multiple science and engineering disciplines.

Figure 31.3 describes influences of anthropogenic and non-anthropogenic scenarios to the relevance of various mission criteria and to the prioritization of communities for strategically addressing coastal erosion in Alaska.

Figure 31.4 describes the variations in ranking of the severity of potential erosion of the coastal communities for each of the several scenarios of climate change.

An example below is described using five of the priority action communities: Chefornak, Kivalina, Newtok, Shaktoolik, and Shishmaref.

In Fig. 31.5, users enter the descriptions of communities. Next, the communities are assessed according to each criterion. Figure 31.6 shows a sample of the assessment for

Criteria	Scenarios: Baseline S00	Sea level rise > 1m S01	Decrease in sea ice S02	Storm surge + Increased erosion S03	Sea level rise < 1m S04
Critical Infrastructure (School, Utilities, Transportation)	Baseline relevance of criteria (no change)	Small Increase		Small Increase	
Human Health and Safety					
Subsistence and Shoreline Use being Limited		Large Increase	Small Increase		Small Increase
Community Setting/Geographic Location					
Housing and Population				Small Increase	
Housing in Parallel					
Environmental Hazard					
Cultural Importance					
Commercial/Non-Residential		Small Increase	Small Increase		

Fig. 31.3 Influences of climate and other scenarios to the relevance of strategic criteria for addressing coastal erosion in Alaska

the five communities. Because Chefornak, Alaska, has schools and houses endangered by the coastal erosion ranging from 50 to 100 ft from the shoreline, critical infrastructure was assessed at medium impact [77]. Medium impact is represented by a hollow circle, minimal or no impact is represented by a blank cell, and high impact is represented by a filled circle.

Next, the influence of the climate scenarios are selected to reflect the degree of impact of the criteria on the scenarios. Figure 31.6 reflects how relevance of criteria is influenced by the scenarios. This key step is the particular innovation of this approach.

For example, the scenario, "Sea level rise >1 m," is determined to result in a small increase in impact on critical infrastructure. This increase is relative to the baseline scenario (Fig. 31.7).

The results of the five communities are analyzed to yield insight to the influence of the scenarios. Figure 31.8 indicates that the top-ranked community according to the baseline scenario is Kivalina. The Kivalina community is of relatively more concern for erosion across the relevant criteria in comparison to the other communities.

Figure 31.9 shows that the variation in damage score due to the influence of the climate scenarios is represented as a range of scores around the baseline. Kivalina has the greatest baseline damage score and the greatest range of impact possibilities under the scenario combinations. The baseline score of Shaktoolik also represents the condition of least impact under the scenario combinations.

The scenarios are ordered according to their influence on the ranking of communities, with the "Sea level rise >1 m" scenario having the highest influence, as shown in Fig. 31.10. This scenario therefore, has the greatest influence on changing the baseline damage score. Conversely, "Increase in sea ice" has the lowest influence, as shown in Fig. 31.11. This scenario is interpreted to have the lowest influence on changing the baseline damage. The results of this analysis are useful for prioritizing communities and emergent conditions with a need for erosion protection. The analysis helps determine what scenarios or combinations of scenarios of climate change

Scenarios	Baseline	Sea level rise > 1m	Decrease in sea ice	Storm surge + Increased erosion	Sea level rise < 1m	Increase in sea ice	Increased Flooding	Decreased erosion	Best Rank	Worst Rank	Average Rank
Barrow, AK	11	13	12	16	10	7	11	15	7	16	11
Chefornak, AK	8	9	2	6	7	11	9	10	2	11	7
Chevak, AK	6	4	6	5	5	9	8	7	4	9	6
Clarks Point, AK	9	8	16	17	9	4	4	6	4	17	10
Cordova, AK	3	6	15	10	3	14	3	3	3	15	8
Deering, AK	14	17	18	20	19	20	10	8	10	20	17
Dillingham, AK	21	21	21	21	22	18	20	20	18	22	21
Emmonak, AK	14	18	11	9	13	15	16	13	9	18	14
Golovin, AK	4	5	7	3	4	3	4	4	3	7	4
Husila, AK	18	10	10	15	15	21	19	19	10	21	15
Kivalina, AK	1	1	1	1	1	1	1	1	1	1	1
Kotlik, AK	2	1	4	2	2	2	2	1	1	4	2
Lime Village, AK	21	21	21	21	21	18	20	20	18	21	20
McGrath, AK	16	19	13	13	17	16	15	16	13	19	16
Newtok, AK	17	7	8	8	8	5	7	8	5	8	7
Nunapitchuk, AK	10	12	9	11	11	6	12	10	6	12	10
Port Heiden, AK	16	15	13	13	17	17	18	14	13	18	16
Saint Michael, AK	18	16	19	12	15	10	16	17	10	19	15
Selawik, AK	20	20	20	19	20	22	22	22	19	22	20
Shaktoolik, AK	11	13	17	7	12	12	14	12	7	17	12
Shishmaref, AK	5	3	5	4	6	8	6	5	3	8	5
Unalakleet, AK	13	11	3	18	14	13	13	18	3	18	12

Fig. 31.4 Sensitivity of the rankings of Alaska communities to the various scenarios of emergent conditions

Project	Description
Cherfornak, AK	A second class city with a population of 460 people locat It is located within the Clarence Rhode National Wildlife F
Kivalina, AK	Kivalina is located at the tip of an 8 mile barrier reef betw 8.6 inches, with 57 inches of yearly snowfall. The averag degrees Fahrenheit in July.
Newtok, AK	Newtok is located on the Ninglick River, 94 miles northwe mile of water. The average precipitation is 17 inches, wit 59 degrees Fahrenheit, and winter temperatures range fr
Shaktoolik, AK	Shaktoolik is a second class city located on the eastern s Unalakleet. It has a population of 214 and is located on a Norton Sound.
Shishmaref, AK	Shishmaref is on Sarichef Island in the Chukchi Sea, 5 r National Heritage Park endorsed by Presidents Bush anc Fahrenheit and winter temperatures -12 to 2 degrees Fah

Fig. 31.5 Community descriptions. This figure shows where the user inputs each community and a corresponding description

	Critical infrastructure	Human health and safety	Subsistence and shore line use being limited	Community setting
Cherefornak, AK	○		●	○
Kivalina, AK	●	○	●	●
Newtok, AK	○	○	●	●
Shaktoolik, AK	●		○	○
Shishmaref, AK	●		○	●

Fig. 31.6 Assessment impact values. This figure shows where the user rates the impact level for each community

are influential for individual communities. With this information, the residents of these communities, their local governments, scientific experts, policy makers, and various other stakeholders are able to make evidence-based strategic decisions resulting leading to robust adaptive management of erosion.

Criteria	Scenarios: Baseline S00	Sea level rise > 1m S01	Decrease in sea ice S02
Critical Infrastructure (School, Utilities, Transportation)	Baseline relevance of criteria (no change)	Small Increase	
Human Health and Safety			
Subsistence and Shoreline Use being Limited		Large Increase	Small Increase
Community Setting/Geographic Location			
Housing and Population			
Housing in Parallel			
Environmental Hazard			
Cultural Importance			
Commercial/Non-Residential		Small Increase	Small Increase

Fig. 31.7 Scenario adjustments. The influence of the climate and other scenarios to the relevance of the performance criteria for adaptation

Baseline Statistics	
Ordered Projects	Rank
Kivalina, AK	1
Newtok, AK	2
Shishmaref, AK	3
Cherfornak, AK	4
Shaktoolik, AK	5

Fig. 31.8 Baseline rankings of projects. The rankings of the five communities under the baseline scenario, where climate change and other emergent conditions are not yet considered

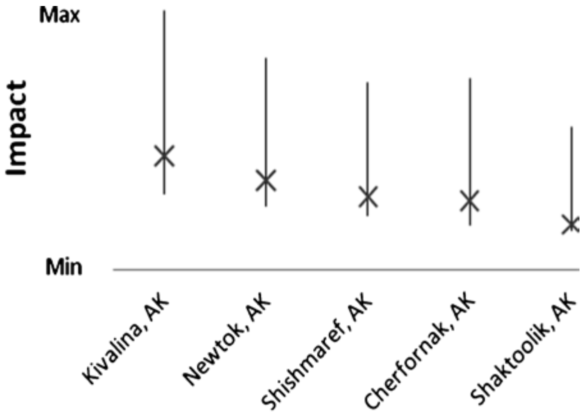

Fig. 31.9 Baseline score with scenario impact. The range of erosion-severity scores for five communities with respect to the influence of scenarios, where the "X" represents the baseline (no-scenarios) score

Fig. 31.10 The most influential of the seven developed scenarios

Scenarios	Rank
Sea level rise > 1m	1
Increased Flooding	2
Decrease in sea ice	3

Fig. 31.11 The least influential of the seven developed scenarios

Scenarios	Rank
Sea level rise < 1m	5
Decreased erosion	6
Increase in sea ice	7

31.4 Case of Energy Security of Inland Installations with Need for Climate Adaptation

Military and industrial facilities need secure and reliable power generation. Grid outages can result in cascading infrastructure failures as well as in security breaches and should be avoided. Adding redundancy and selecting reliable, environmentally friendly, and cost-effective energy sources can require additional financial, environmental, and logistical considerations and resources. Uncertain scenarios involving future environmental conditions, regulatory changes, and growth of regional energy demands result in further complications. This paper integrates a scenario-informed analysis to a multicriteria decision analysis to evaluate energy and environmental security investments for industrial and military installations. Typically, hundreds of grid outages in a year threaten to result in cascading failures, loss of productivity, and mission degradation. It is important to reduce the number and duration of these outages and the development of alternative energy supply and distribution capabilities. Adding redundant equipment requires significant financial, environmental, and logistical considerations and resources, but emergent conditions can jeopardize performance efficiency. For a military or industrial installation or facility, these emergent conditions include but are not limited to future environmental and climatic conditions, regulatory changes, and evolving power demands. Future scenarios add complexity to achieving various energy and environmental security goals that are considered when selecting alternative energy sources and technologies. These goals include accomplishing critical mission objectives, integrating multiple fuel sources, reducing energy consumption and disruptions, reducing foreign energy inputs, and using renewable resources [39, 53, 71–73]. Related concerns include the preferences of stakeholders, cultural considerations, fluctuating energy costs, base integration, and aging buildings and equipment.

Diverse emergent conditions including climate change can significantly affect the prioritization of energy alternatives for installations. Combining future geographic, regulatory, geopolitical, environmental, and other conditions results in diverse future scenarios [15, 40, 55, 69, 70, 81]. Table 31.2 describes emergent conditions that may

Table 31.2 Diverse emergent conditions that may combine with climate change to influence energy security of inland/terrestrial installations

	Scenarios				
Emergent conditions in addition to climate change	s_1	s_2	s_3	s_4	s_5
Large carbon emissions tax					
Large government subsidies for renewable energy				+	
Reemergence of nuclear technology					
Abandonment of nuclear technology					
Newly established Renewable Portfolio Standards					
Short-term national/regional energy blackout					
Long-term national/regional energy blackout					
Increased volatility in oil and gas prices and supply			+		
Oil and gas remain available and cost-effective	+				
Deterioration in geopolitics and war/peace/terrorism					+
Few changes in geopolitics and war/peace/terrorism					
Improvement in geopolitics and war/peace/terrorism					
Attack on national power grid					
Low growth in energy technology					
Moderate growth in energy technology					
High growth in energy technology		+			
Low environmental-movement impacts					
Moderate environmental-movement impacts					
High environmental-movement impacts				+	
Low national economic growth					
Moderate national economic growth					
High national economic growth		+			
Early realization of climate change					
National switch to solar energy					
Increase in National/International demand for energy and environmental security			+		
Stimulated demand for distributed energy					
Increase in demand for domestic energy sources			+		
Accelerated commercialization of renewable energy		+			
Aggressive public investment in R&D in hydrogen and fuel cell technologies		+			
Prolonged drought/Inclement weather					
Improved battery technology					
Switch to SmartGrid Technologies					
Changing demand for food-based agriculture					

combine with climate change to affect energy security of installations. For an installation or industrial facility, the scenarios can include local, regional, national, and international emergent conditions. National and international technology-related conditions include the immediate, unforeseen shifts in energy technologies related to new nuclear technologies, coal technologies, or promising renewable energy technologies. Political and regulatory conditions include new energy guidelines and incentives. Some examples include future carbon legislation [65], renewable energy credits, and alternative regulatory pricing structures. International conditions include shifts in the geopolitical power relating to fossil fuels and natural gas that influence availability and costs of these energies. Conditions at the installation or facility level that can impact mission execution include local disruption of energy services caused by commercial energy grid failures, destruction of energy systems or terrorism, and deterioration of other infrastructures. Other conditions involve weather and climate, fuel and material supply chains, institutional and organizational issues, and changing security requirements. While some conditions or scenarios are factually and scientifically based and mutually agreed among stakeholders, others may reflect advocacy positions or specialized points of view. For a particular installation or facility, a commitment to energy and environmental security calls for a prioritization of investment alternatives that is informed by analysis of emergent conditions. An energy and environmental security plan that secures reliable energy and strives for energy, environmental, and other goals should account for tradeoffs and preferences of diverse stakeholders.

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