Water Working Notes

Note No. 28, November 2010

FLOWING FORWARD

FRESHWATER ECOSYSTEM ADAPTATION TO CLIMATE CHANGE IN WATER RESOURCES MANAGEMENT AND BIODIVERSITY CONSERVATION

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WATER
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ACKNOWLEDGMENTS

This report has been funded by the World Bank and World Wildlife Fund (WWF). The World Bank's support came from the Environment Department; the Energy, Transport, and Water Department; and the Water Partnership Program. WWF's support came through the HSBC Climate Partnership. This knowledge product supports two World Bank sector analyses: (1) the Climate Change and Water Flagship analysis that has been developed by the Energy, Transport, and Water Department Water Anchor (ETWWA), and (2) the Biodiversity, Climate Change, and Adaptation economic and sector analysis prepared by the Environment Department (ENV). It is also a contribution to the 2010 International Year of Biodiversity.

Rafik Hirji, the World Bank task team leader, provided the overall intellectual and operational guidance to its preparation. The task team is grateful to Vahid Alavian and Michael Jacobsen, the former TTL and current TTL of the Climate Change and Water sector analysis; and Kathy Mackinnon, the TTL for the Biodiversity, Climate Change, and Adaptation sector analysis; as well as Abel Mejia, Julia Bucknall, and Michele de Nevers, managers of ETWWA and ENV, for supporting the preparation of this report. WWF is grateful for HSBC's support of its global freshwater program through the Partnership. The HSBC Climate Partnership is a five-year global partnership among HSBC, The Climate Group, Earthwatch Institute, The Smithsonian Tropical Research Institute, and WWF to reduce the impacts of climate change for people, forests, water, and cities.

Unless otherwise stated, all collaborators are affiliated with WWF. The report originally grew out of ideas in a white paper prepared by John Matthews and Tom Le Quesne (2009) but reflecting the extensive discussions of many others, including Bart (A.J.) Wickel, Guy Pegram (Pegasys Consulting), and Joerg Hartmann. This report was drafted through a complex process under the coleadership of Tom Le Quesne and John H. Matthews. Rob Wilby (Loughborough University) led efforts for early background content on climate science and adaptation principles. The Breede and Okavango case studies were substantially led by Constantin Von der Heyden (Pegasys Consulting) and Guy Pegram. The Siphandone–Stung Treng case was led by Elizabeth Kistin (Duke University) and Geoffrey Blate, with additional support from Peter McCornick (Duke University). Glauco Kimura de Freitas led the Tocantins-Araguaia case, with support from Samuel Roiphe Barreto and Carlos Alberto Scaramuzza. Carla Guthrie (University of Texas) provided significant insights into vulnerability assessment, and Catherine McSweeney (GTZ) clarified multilateral institutional arrangements. Eliot Levine provided significant support for managing authors, versions, and reviewers. Nikolai Sindorf was instrumental in assisting with hydrological perspectives and basin images.

Early reviewers included Robin Abell, WWF-US; Dominique Bachelet, Oregon State University; Cassandra Brooke, WWF-Australia; Ase Johannessen, International Water Association; Robert Lempert, RAND Corporation; James Lester, Houston Advanced Research Center; Peter McCornick, Duke University; Guillermo Mendoza, US Army Corps of Engineers; Jamie Pittock, Australian National University; LeRoy Poff, Colorado State University; Prakash Rao, Symbiosis International University; Nikolai Sindorf, WWF-US; Hannah Stoddart, Stakeholder Forum for a Sustainable Future; and Michele Thieme, WWF-US.

Final peer reviewers included Greg Thomas, president, Natural Heritage Institute; Brian Richter, coleader of the Freshwater Program, the Nature Conservancy; and Mark Smith, head of the Water Program, International Union for the Conservation of Nature. World Bank peer reviewers during this stage included Glenn-Marie Lange, senior environmental economist, ENV; and Nagaraja Rao Harshadeep, senior environmental specialist, AFTEN. Gunars Platais, senior environmental economist, LCSEN, provided verbal comments. Written comments were also received from Charles Di Leva, chief counsel, and Nina Eejima, senior counsel, LEGEN. The authors are particularly grateful for an in-depth review from Dr. Richard Davis and for the administrative support provided by Doreen Kirabo, program analyst.

The approving manager at the World Bank for this work is Julia Bucknall.

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EXECUTIVE SUMMARY

CLIMATE CHANGE AND FRESHWATER ECOSYSTEMS

Freshwater ecosystems provide a range of services that underpin many development objectives, often for the most vulnerable communities in society. These include provisioning services such as inland fisheries, and regulating services such as waste assimilation; sediment transport; flow regulation; and maintenance of estuarine, delta, and near-shore marine ecosystems. Repeated global surveys such as the Millennium Ecosystem Assessment and *Global Biodiversity Outlook 3* have identified freshwater ecosystems as having suffered greater degradation and modification than any other global ecosystem, resulting in significant negative impacts on freshwater ecosystem services. A new UNEP report titled *Dead Planet, Living Planet: Biodiversity and Ecosystem Restoration for Sustainable Development* (UNEP, 2010) underscores the huge economic benefits that countries might accrue through restoration of wetlands, river and lake basins, and forested catchments.

Under current climate projections, most freshwater ecosystems will face ecologically significant climate change impacts by the middle of this century. Most freshwater ecosystems have already begun to feel these effects. These impacts will be largely detrimental from the perspectives of existing freshwater species and of the human livelihoods and communities that depend upon them for fisheries, water supply and sanitation, and agriculture. There will be few if any "untouched" ecosystems by 2020, and many water bodies are likely to be profoundly transformed in key ecological characteristics by mid-century.

Not all freshwater ecosystems will be affected in the same way by climate change. The pace and type of climate change will vary by region and even across segments of a single basin. The uneven nature of climate change impacts means that we must also understand the differential climate vulnerability, sensitivity, and hydrological importance of different aspects of a basin in order to prioritize management responses. In effect, climate change will lead to a tapestry of differential risks across freshwater systems. Particular elements of the ecological system will be at risk at particular points in time and space, and to particular kinds of changes or stressors. For example, headwater streams are more likely to be vulnerable to low-flow impacts than are larger main stems of river systems. Systems may be at risk for only a short period of the year or during drought years.

The impacts of climate change on freshwater ecosystems will be complex and hard to predict. These impacts will lead to changes in the quantity, quality, and timing of water. Changes will be driven by shifts in the volume, seasonality, and intensity of precipitation; shifts from snow to rainfall; alteration of surface runoff and groundwater recharge patterns; shifts in the timing of snowpack melting; changes in evapotranspiration; increased air and water temperatures; and rising sea levels and more frequent and intense tropical storm surges. Together, these will lead to a number of key eco-hydrological impacts on freshwater ecosystems:

- Increased low-flow episodes and water stress in some areas
- Shifts in the timing of floods and freshwater pulses
- Increased evaporative losses, especially from shallow water bodies
- Higher and/or more frequent floods
- Shifts in the seasonality and frequency of thermal stratification of lakes
- Saltwater encroachment in coastal, deltaic, and low-lying ecosystems, including coastal aquifers
- Generally more intense runoff events leading to increased sediment and pollution loads
- Increased extremes of water temperatures

Changes to the freshwater flow regime will be the most significant and pervasive of the impacts of climate change on freshwater ecosystems. Ecologists are increasingly focusing on freshwater flow regimes as the determinant of freshwater ecosystem structure. Changes to the volume and regime of freshwater flows are already a leading driver of global declines in freshwater biodiversity, and the impacts of climate change are likely to accelerate this pressure. Changes to water ***timing*** as much as changes to total annual runoff are likely to have the most significant impact freshwater ecosystems. As precipitation and evapotranspiration regimes continue to alter, they will alter many aspects of water quality and quantity.

Freshwater systems that already experience or are vulnerable to water stress are likely to be the most sensitive to climate change. This sensitivity may be a function of total annual water stress across the basin but more often will result from seasonal and/or localized vulnerability to water stress.

The pace of climate change will be uneven and sudden rather than gradual and smooth. In most regions currently, climate change impacts are manifested through shifts in the severity and frequency of extreme events such as intense precipitation events and more powerful tropical cyclones, droughts, and floods. The accumulation of impacts will eventually transform many ecosystems in fundamental ways, such as altering permanent streams and rivers to regularly intermittent bodies of water. These shifts in ecosystem state will be very stressful for both freshwater species and for humans dependent on these ecosystems and their resources. In many cases, state-level transformations will occur in a matter of a few years or less.

Impacts on ecosystems will be manifest both through dramatic state shifts as "tipping points" are reached and through gradual deterioration. Certain ecological systems respond to changes in pressure, such as from climate change, in dramatic ways that constitute wholesale shifts in their basic structure. For example, when nutrient levels exceed a certain threshold, some water bodies change from vegetation-dominated to algal-dominated systems where algal blooms and anoxic events occur. Other systems will undergo slow, steady degeneration in the face of climate change. For example, increased water temperatures and reduced flow levels may lead to a decrease in the quantity and diversity of invertebrate species in a system, exacerbating declines in fish populations.

In the majority of cases, damage to freshwater ecosystems will occur as a result of the synergistic impacts of climate change with other anthropogenic pressures. In most cases, climate will not be the predominant driver of freshwater biodiversity loss over the next half century. It is imperative, therefore, that climate impacts be understood as part of the broader set of pressures impacting freshwater systems.

There is a high degree of uncertainty in using global climate models to predict the impacts of climate change on freshwater ecosystems decades into the future. Even on an annual scale, there is considerable divergence in the predicted precipitation patterns from different global climate models. This uncertainty will be even greater on the shorter time scales that are likely to be most important for ecosystems. When these uncertainties in precipitation are fed into complex hydrological and biological models, predictions of climate change impacts on ecosystems become even more uncertain.

The Role of Risk and Vulnerability Assessment

There are opportunities to undertake assessments of vulnerability to climate change in a range of planning activities and operations. Strategic environmental assessment of climate change vulnerability should be undertaken through national water sector policy formulation, water resources planning and water sector program development.

Attempts to assess and respond to climate change should adopt a risk-based approach rather than focus on impact assessment. The considerable uncertainty about ecosystem impacts of climate change means that attention should be focused on using scenario analysis to identify those ecosystems that are most sensitive to and at risk from change rather than relying only on the development of deterministic predictions of impacts.

The case studies undertaken for this report demonstrated that it is possible to produce useful results on reasonably tight resources and within a short time frame. Achieving this successfully depended upon creating a team with the appropriate range of skills and drawing on the results of existing analyses. While the investment of further resources in the case studies would have enabled greater specification of a number of aspects of risk, it probably would not have created significantly greater certainty about future outcomes given the inherent uncertainties associated with the estimation of future climate impacts on freshwater.

A FRAMEWORK AND MANAGEMENT OBJECTIVES FOR FRESHWATER ECOSYSTEM ADAPTATION

Adaptation requires that an iterative, risk-based approach to water management be adopted. Adaptation responses should be based on risk assessment and adaptive management. This can represent a significant shift away from more deterministic methods that focus on quantifying specific impacts using model-based water resource management approaches. In the context of uncertainty, robust adaptation can be achieved through three adaptation responses: ***shaping*** strategies that implement measures for identified risks, ***hedging*** strategies that enable responses to potential but uncertain future risks, and ***signposts*** that develop targeted monitoring capacity to identify emerging change.

Future climate change implies the need to give increased weight to maintenance of ecosystem functions in the trade-offs inherent in development decision making. The maintenance of freshwater ecosystems has always implied the need to account for trade-offs, particularly in development decision making. However, uncertainty about future climate trajectories creates the need to ensure that ecosystems have both the resilience and flexibility to respond to change. This implies the need to accommodate significant additional assimilative capacity in ecosystems.

In many cases, current methods for planning and managing freshwater resources are likely to result in water infrastructure that makes it harder for freshwater ecosystems to respond to climate change. Climate-sustainable water management is likely to be more conservative, span multiple climate futures, and explicitly build in decision-making processes that allow operations and future construction to be flexible across a range of climate parameters.

There are three key management objectives that underpin any response to climate change impacts on freshwater ecosystems. There are opportunities for the Bank to provide support to each of these objectives:

1. Sufficient institutional capacity and appropriate enabling frameworks are essential preconditions for successful climate adaptation. Required institutional capacity can be characterized in terms of enabling frameworks and institutions, such as a functioning and adaptive water allocation mechanism, effective and functioning water management institutions, opportunities for stakeholder involvement, and sufficient monitoring, evaluation and enforcement capacity.

2. Maintenance of environmental flows is likely to be the highest-priority adaptation response for freshwater ecosystems, in particular in regulated or heavily abstracted river systems. This requires policies and implementation mechanisms to protect (and, if necessary, restore) flows now, and to continue to provide environmental flow regimes under changing patterns of runoff. Water for the environment needs to be assigned a high priority in government (water or environment) policy if environmental flows are to be protected in the face of changing flow regimes.

3. Reducing existing pressures on freshwater ecosystems will reduce their vulnerability to climate change. Measures to protect ecosystems so that they have sufficient absorptive capacity to withstand climate stressors include reducing extractive water demands from surface and groundwater; restoring more natural river flows so that freshwater ecosystems are not vulnerable to small, climate-induced changes in runoff; and reducing other pressures such as pollution and overfishing. The assimilative capacity of freshwater ecosystems will be further strengthened when a diversity of healthy habitats can be maintained within a river system.

RECOMMENDATIONS FOR INTEGRATION INTO OPERATIONS

Successful adaptation ultimately depends upon the resources, policies, and laws of national, transboundary, and local political and management authorities. There are significant opportunities for supporting client governments in achieving these objectives through the Bank's portfolio of programs, policies, and technical support, within and beyond the water sector. Opportunities within the water sector include program and policy lending at the basin and national levels to improve water-planning processes and provide broader institutional support.

Opportunities also exist outside the water sector, particularly by supporting transboundary, national, and sub-national environmental programs. The potential activities could form important component elements of any future cross-sectoral adaptation support. Where possible, support to freshwater ecosystem adaptation should be integrated with broader support activities in the water sector.

In most cases, improving the ability of freshwater ecosystems to adapt to climate change will not require substantively new measures. Instead it requires renewed attention to the established principles of sustainable water management. Many of the necessary interventions will simultaneously promote environmental and developmental objectives, for example, and also will support increased institutional capacity and strategic planning of water resources.

Project Level

The maintenance and restoration of environmental flows should be strengthened as core issues in the Bank's water infrastructure lending. The recent publication *Environmental Flows in Water Resources Policies, Plans, and Projects* (Hirji and Davis, 2009a) provides recommendations for supporting improved protection of environmental flows across projects, plans, and policies. This document identifies four entry points for Bank engagement, including measures at both project and policy levels. Concerns over climate change and the impacts on environmental flows reinforce the importance of a strong consideration of environmental flow needs in infrastructure development projects. Environmental flow needs should therefore be integrated into the planning, design, and operations of all future infrastructure projects that have the potential to affect flows.

The design, siting, and operation of water infrastructure will be central to determining the extent to which freshwater ecosystems are or are not able to adapt to future climate shifts. There are particular opportunities to account for the potential impacts of climate at three places in infrastructure planning:

- *Impact assessment*: Impact assessment provides the core mechanism by which a full consideration of the impacts of infrastructure on future adaptability and resilience can be considered. This can include assessments of the impacts of climate change on environmental flows, an assessment of potential future shifts in ecosystem and species distribution, and the potential impacts of new infrastructure on the capacity of ecosystems to adapt to these changes.

- *Design*: Design of infrastructure can be crucial in dictating whether, and the extent to which, infrastructure is capable of facilitating adaptation to future climate shifts. In practical terms, this is likely to mean that infrastructure should be designed to be built and operated with more flexibility in order to encompass a number of differential future climate states. Some of the characteristics of infrastructure design that can contribute to the achievement of these objectives include dam design and outlets with sufficient capacity to permit a range of environmental flow releases, multi-level offtakes to control temperature and chemical pollution, permit releases under a range of different conditions, provision of fish passages, and sediment outlets or bypass facilities.

- *Operating rules*: In order to protect environmental flows under conditions of future variability, dam operating rules can include mechanisms to retain flexibility, with specific provisions for the protection of environmental flow needs as water availability changes. The Bank could support the inclusion of these flexible operating rules as a deliberate attempt to test and demonstrate options for managing infrastructure.

Projects and programs to re-operate infrastructure can provide win-win adaptation opportunities while improving economic and environmental performance. This can include alterations to infrastructure design, facilities, and operating rules at the time of re-operation to ensure that any infrastructure provides maximum support to the adaptive capacity of ecosystems, and incorporate mechanisms to allow for flexible operations in the future in response to shifting hydrology. In some cases, the redesign of hydropower facility operating rules can improve generating capacity and improve provisions for environmental flows.

The use of strategic environmental assessment can be an important tool in ensuring that project-level investments support ecosystem resilience and adaptive capacity. The ability of freshwater ecosystems to adapt to climate change is improved where infrastructure projects are designed and operated at a basin and/or system scale. This can provide opportunities for the protection of particularly vulnerable parts of river systems or those that contribute in particular to the functioning and resilience of the overall system. Where the operation of infrastructure across a system is coordinated in an adaptive manner, there is significantly greater flexibility than if individual infrastructure is operated in isolation.

The increased use of strategic environmental assessment provides an important opportunity for integration of risk and vulnerability assessments into the design of infrastructure projects. The 2009 Climate and Water Flagship report (World Bank, 2009) discusses the use of vulnerability assessments for infrastructure projects and recommends that risk assessments be undertaken of projects and their various component parts. There are opportunities to expand the focus of these risk assessments to include an assessment of the vulnerability of freshwater ecosystems and their services to climate change in the context of basin or sub-basin vulnerability.

Program, Policy, and Technical Support

The Bank is well-placed to support client governments to develop their institutional capacity. As identified in the Water Anchor report, strong institutions operating within the right institutional framework constitute the first step toward adapting to changes in climate. As part of this process, appropriate priority should be given to building capacity in monitoring and assessment. This will be crucial to providing water resource management institutions with the information they need to adapt to increased climate variability.

Continued and expanded support to the development of environmental flow policies provides a key opportunity to promote adaptation. The Bank's review of environmental flows (Hirji and Davis, 2009a) identified the potential to promote the integration of environmental flows into developing countries' policies through instruments such as country water resources assistance strategies (CWRASs), country assistance strategies (CASs), and country environmental assessments. The importance of environmental flows for providing the resilience needed for climate change adaptation provides added urgency to this recommendation. Opportunities could be actively identified to encourage and support client governments to put in place the policy and implementation framework for the restoration and maintenance of environmental flows early in the decision-making process.

Support to effective national and basin planning and the strategic environmental planning of water provide opportunities to promote environmental and economic objectives, incorporating informed analysis of trade-offs in decision making. Effective planning of water resources development will be crucial to adaptive water management. A number of important tools, collectively called strategic environmental assessment (SEA), have been developed to support the integration of long-term environmental considerations into transboundary, national, and sub-national water resource policy and planning. An extensive World Bank review of the use of SEA in water resources management included a series of recommendations for the mainstreaming of SEA in the World Bank's water sector work (Hirji and Davis, 2009b). These strategic assessment exercises provide the opportunity to include vulnerability assessments.

Programs of support for resource protection, including pollution abatement, water source protection, and water efficiency activities, provide the potential for a win-win or low-regrets response. Support for these activities can provide immediate social, economic, and biodiversity benefits while increasing freshwater adaptive capacity.

INTRODUCTION

THE CONTEXT FOR THIS REVIEW

The IPCC ***Climate Change and Water Technical Paper*** concluded that observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems (Bates, Kudzewicz, and Palutikof 2008). This implies that development and conservation programs could fail to realize intended benefits or, worse still, contribute to increased exposure of populations to climatic hazards.

This review has been requested by the World Bank from WWF to develop the guiding principles, processes, and methodologies for incorporating anthropogenic climate change within an analytical framework for evaluating water sector projects, with a particular emphasis on impacts on ecosystems. It is a contribution toward the development of a systematic approach to climate change adaptation in the Bank's water and environment sectors.

The findings and recommendations are key contributions to the Bank's two-sector analysis on (1) the Climate Change and Water Flagship that has been developed by the Energy, Transport, and Water Department (ETW), and (2) the Biodiversity, Climate Change, and Adaptation economic and sector analysis prepared by the Environment Department (ENV). This report is also a contribution to the 2010 International Year of Biodiversity.

STRATEGIC FRAMEWORK FOR CLIMATE CHANGE AND DEVELOPMENT

The World Bank Group Strategic Framework has formulated advice on operational responses to the development challenges posed by global climate change (World Bank, 2008). Among several major initiatives, the document envisages routine screening of operations for climate risks to major infrastructure investments with long life spans (such as hydropower and water transfer schemes). The primary focus is on achieving sustainable development and poverty reduction outcomes from national to local levels despite climate risks, rather than on managing environmental change, per se.

The Strategic Framework is intended to inform and support rather than impose actions on the various entities of the World Bank Group. Hence, the guiding principles point operational divisions toward suitable tools, incentives, financial products, and measures to track progress. Despite rapid growth in scientific and economic knowledge about climate development risks, it is recognized that there is no decision-making framework for handling multiple trade-offs and uncertainties, for example between energy investments and biodiversity or water management. Therefore, the Framework places strong emphasis on flexibility and capacity building to ensure that there is learning by doing. Any technical assistance should be customized to meet local needs.

Given the large uncertainties in climate risk assessment, not least due to limited agreement in regional predictions from climate models, the first action area of the Framework focuses on financial and technical assistance to vulnerable countries impacted by current climate variability (floods, droughts, and tropical cyclones). The underlying principle is that "low regret" actions should yield benefits regardless of future climate policies and risks. In reality, such actions tend to be "low regret" because of either incremental or opportunity costs arising from the strengthening of climate adaptation and climate mitigation components of development projects.

Climate Change and Water

World Bank water sector investments will total US$10.6 billion in FY09–10. Of these, over 30 percent have been identified as having high exposure to risk from climate-induced changes to runoff by the 2030s. The Energy, Transport, and Water Department has prepared an AAA Flagship on water and climate change as a strategic response to climate change in the water sector. This Flagship includes a main report and a series of supporting technical reports and papers (World Bank, 2009). The supporting reports include a synthesis of the science as related to climate and the hydrologic cycle, an analysis of climate change impacts on groundwater resources and adaptation options, a common platform of climate change projections and methodology for assessment of the vulnerability of water systems to hydrologic changes, a review of the Bank's current water investment portfolio to determine the extent to which climate change is considered at the project-design level, an evaluation of the exposure of the World Bank water sector investments, and strategies for water and wastewater service providers. The Flagship also developed a range of adaptation options for increased robustness and resiliency of water systems to climate variability, a framework for risk-based analysis for water investment planning, and recommendations on how the Bank can incorporate climate change into its water work.

The current report is one of these Flagship support papers. It applies key lessons and insights from the Flagship analysis to freshwater ecosystems and provides recommendations on how these lessons and insights can be incorporated into ongoing Water Anchor processes and activities. It does not provide a comprehensive survey of the projected impacts of climate change on water resources and the water sector or of the current state of scientific knowledge concerning these impacts.

The Flagship report provides extensive guidance on existing and potential adaptation responses for the water sector, including risk assessment approaches and options for integration of climate adaptation into project, program, and policy lending and support. It includes a preliminary discussion of the potential impacts of climate change on freshwater ecosystems. The current report extends this preliminary discussion to the provision of specific recommendations on adaptation measures for these ecosystems.

Water and Environment

The World Bank has developed a program of work on the incorporation of ecosystems and sustainability into water sector policy and lending to support the implementation of the Bank's Environment Strategy and Water Resources Sector Strategy. This work is based on the understanding that freshwater ecosystem integrity is essential to the maintenance of a wide range of goods and services that underpin livelihoods of communities in developing countries.

As part of this increasing program of work, the World Bank has developed guidance on a number of the key mechanisms that will be important for climate adaptation. Two of the most important considerations for protecting freshwater ecosystems are ensuring provisions for environmental flows and undertaking strategic assessment of water resource development projects, plans, and policies. Two recent World Bank sector analyses provide a strong basis for action in these areas:

- ***Environmental Flows in Water Resources Policies, Plans, and Projects*** (Hirji and Davis, 2009a). The report reviews environmental flow implementation at a variety of levels based on 17 international case studies. The report recommends strengthened Bank capacity in environmental flow assessments, strengthening of environmental flow assessment in lending operations, promotion of environmental flows in policies and plans, and an expansion of collaborative partnerships.

- *Strategic Environmental Assessment: Improving Water Resources Governance and Decision Making* (Hirji and Davis, 2009b). Based on a review of 10 case studies, this report produced recommendations for the use and promotion of SEA as a tool across World Bank water resources activities. The case studies covered a range of water-related sectors, including water supply/sanitation; hydropower; water resources; and the environment at strategy, program, and plan levels.

Biodiversity, Climate Change, and Adaptation

The World Bank has a large and growing portfolio of investment in biodiversity conservation. Between 1988 and 2008, the World Bank group committed almost $3.5 billion in loans and GEF grants and leveraged $2.7 billion in co-financing, resulting in a total investment portfolio exceeding $6 billion (World Bank, 2010a).

This body of work includes considerations of how biodiversity investments can adapt to climate change and how investments in biodiversity conservation can make an important contribution to broader climate adaptation efforts for livelihood security. A recent World Bank review, ***Convenient Solutions to an Inconvenient Truth: Ecosystem-based Approaches to Climate Change*** (World Bank, 2010a), provided a range of options for using biodiversity investment to support adaptation and mitigation efforts, with a particular emphasis on the role of protected areas and forest conservation. The recommendations in the current report adopt and apply these results to freshwater ecosystems.

Objectives, Approach, and Methodology

This report has two primary objectives:

- To broaden the understanding of climate change impacts on freshwater ecosystems and the ecosystem services that many communities depend on

- To recommend a structured approach (policy and operational guidance) for factoring the ecosystem implications of climate adaptation into integrated water resources planning, design, and operational decisions, as well as biodiversity conservation programs

The overall report has been developed through a three-stage process. In the first stage, a framework for the analysis of climate vulnerability in ecosystems was developed through a review of existing literature and approaches. In the second stage, this framework was trialed through a series of case studies: an in-depth case study of the Okavango wetland, accompanied by case studies of the Breede (South Africa) and the Mekong and Tocantins-Araguaia (Brazil) river basins. In the third stage, results and conclusions from these case studies were used to refine the vulnerability assessment methodology and to develop detailed recommendations for operations.

The detailed recommendations are divided into two parts. The first part provides three key management objectives for resource managers and policy makers who want to build adaptability into freshwater ecosystems. These are based on the expert review and the case study process. The second part describes intervention opportunities for the Bank to support the achievement of these objectives.

Organization of the Report

This report comprises four chapters. Chapter 1 briefly reviews the role and contribution of ecosystem services to development objectives. Chapter 2 describes the current scientific understanding of the potential impacts of climate change on freshwater ecosystems. Chapter 3 sets out a detailed methodology for undertaking vulnerability and risk assessment in the context of freshwater ecosystems and provides a synthesis of the main findings of the case studies that were undertaken in preparation of this report. Chapter 4 provides recommendations for integrating adaptation responses into project and program lending. Short case study illustrations are used throughout the report. Some of these are drawn from the case studies undertaken for this report; others are taken from other independent works to illustrate key points and principles.

1. THE ROLE OF FRESHWATER ECOSYSTEM SERVICES

1.1 FRESHWATER ECOSYSTEM SERVICES

The role of freshwater ecosystem services in providing a range of goods and services that underpin development is increasingly being recognized. Many of these services underpin core development and livelihood objectives, often for the poorest and most marginalized groups in societies. Thus, maintaining healthy ecosystems is not a luxury for the wealthy sectors of society but rather an intrinsic part of providing support for those who are reliant on the environment for their livelihoods. In effect, it is maintaining natural infrastructure, equivalent to constructing and maintaining the built infrastructure that provides technological services for society. Unfortunately, the role that healthy freshwater systems play, both in terms of ecosystem services and in acting as the resource base upon which a range of freshwater services are based, is often identified only when these systems have been degraded or lost.

Decisions on how to allocate access to water resources should always be carried out in a way that distributes the benefits efficiently and equitably. Many of the benefits from protection of freshwater ecosystems cannot be valued easily in economic terms. This means that a triple bottom-line approach will be needed where the benefits are measured in social, environmental, and economic terms. The point here is that environmental outcomes are not separate from other benefits but should be seen as having a legitimate call on water resources when trade-off decisions are being made.

A wide range of different approaches have been used for characterizing ecosystem services, with an increasing number building on the approach adopted by the Millennium Ecosystem Assessment (Millennium Assessment, 2005). This provided a comprehensive framework for the description of the broad range of services provided by functioning ecosystems, dividing services into provisioning services, regulating services, and cultural services. Freshwater systems provide significant systems in each of these categories. The Millennium Ecosystem Assessment provided one of many thorough attempts to survey and evaluate these services, and there are significant ongoing efforts to build on this work (Layke, 2009). It is not the role of this report to repeat or replicate these surveys but rather to provide an illustrative indication of some of the key findings of this and related work.

Provisioning Services

The Millennium Ecosystem Assessment identifies the principal provisioning services associated with freshwater ecosystems (see table 1.1 below).

Various attempts have been made to provide valuation of these services (Costanza et al, 1997, Postel and Carpenter, 1997). The methodologies and approaches behind these studies have been the subject of considerable discussion and debate, with the broad range of values reflecting significant methodological differences. The just-released UNEP Report ***Dead Planet, Living Planet:***

Table 1.1: Selected provisioning services from inland waters (Millennium Assessment, 2005). Freshwater resources are on occasion considered as bridging the gap between provisioning and regulating services.

Provisioning Services	
Food	• Production of fish, wild game, fruits, grains, etc.
Fiber and fuel	• Production of logs, fuelwood, peat, fodder
Biochemical	• Extraction of materials from biota
Genetic materials	• Medicine, genes for resistance to plant pathogens, ornamental species, etc.
Biodiversity	• Species and gene pool

Biodiversity and Ecosystem Restoration for Sustainable Development (UNEP, 2010) has also highlighted the huge economic benefits that countries might accrue through restoration of wetlands, river and lake basins, and forested catchments. Whatever the accuracy and utility of these global valuations, more specific examples can provide clear demonstrations of the value of these services, and many are available.

Freshwater fisheries provide one of the most significant freshwater services around the globe. In sub-Saharan Africa, for example, Lake Malawi/Nyasa provides 70 to 75 percent of animal protein consumed in Malawi, while Lake Victoria has historically supported the world's largest freshwater fishery, yielding 300,000 tons of fish a year worth $600 million. Similarly, in Southeast Asia, the Mekong fishery is a regionally significant source of livelihoods and protein. An estimated 2 million tons of fish and other aquatic animals are consumed annually in the lower Mekong basin alone, with 1.5 million tons originating from natural wetlands and 240,000 tons from reservoirs. The total value of the catch is about $1.2 billion (Sverdrup-Jensen, 2002). The Tonle Sap fishery alone on the Mekong system provides 230,000 tons a year of fish (ILEC, 2005).

These benefits can be locally highly significant, particularly for some of the planet's most vulnerable communities where fish is often the only source of animal protein to which communities have access (Kura et al., 2004). The Siphandone and Stung Treng areas of the Mekong basin are one of the case study locations used in this study. Poverty levels within both areas are high. In Mounlapamok district, where the Siphandone area lies, between 40 and 50 percent of households fall below the village-level poverty line (Epprecht et al., 2008). While market exposure and access are growing, there is very little commercial or industrial production in the Siphandone–Stung Treng area. As a result, individuals and communities within the area depend heavily on subsistence cultivation and fishing (Try and Chambers, 2006). According to the International Union for Conservation of Nature (IUCN, 2008), roughly 80 percent of households in southern Lao PDR participate in wild-capture fisheries, which in turn contribute 20 percent of gross income in the area (IUCN, 2008b).

Regulating Services

The regulating services of freshwater ecosystems are pervasive and being increasingly recognized as freshwater systems degrade, leading to loss of these services. Services such as the waste assimilative capacity of freshwater systems or recharge of groundwater reserves as a result of the inundation of floodplain wetlands may not receive the recognition that they merit until they are lost (Table 1.2).

Many of these regulating services are associated with specific elements of the flow regime and can be impacted in different ways by different modifications to that regime. Waste assimilative capacity is typically impacted by increasing water stress, for example, while the ability of freshwater systems to maintain sediment transport or groundwater recharge may be more dependent on flood or pulse events.

Significant localized and regional examples can serve to illustrate the broader developmental importance of these services as part of water resources management planning and projects. From mid-May to early October, flows of the Mekong River system become so great that the Mekong

Table 1.2: Key regulating services of freshwater systems

Regulating Services	
Flow regulation	• Storage and release of flood peaks in wetlands; recharge of groundwater
Sediment transport	• Maintenance of river channel, wetland, and estuary form and function; provision of sediment to near-shore environments; replenishment of wetland and floodplain sediment
Flows to marine systems	• Maintenance of coastal, delta, and mangrove ecosystems; prevention of saline intrusion in coastal and estuarine regions
Waste assimilation	• Retention and removal of pollutants and excess nutrients; filtering and absorption of pollutants

delta can no longer support the required volumes, and the flows back up the Tonle Sap River and fill the Tonle Sap Lake system and surrounding floodplain. As noted above, this inundation supports one of the most productive freshwater fisheries in the world. However, this process also provides vital regulating services as the flood waters reverse and flow out of Tonle Sap and into the Mekong Delta as the volume of water flowing down the main Mekong channel declines. This crucially permits a second rice crop and controls saline intrusion into the delta (ILEC, 2005).

In the Siphandone area of the Mekong, there is limited year-round agricultural land. However, as a consequence of the flow patterns and sediment transport of the river, hundreds of kilometers of riverbanks and exposed alluvial deposits in the area are used to cultivate extensive seasonal vegetable gardens (Daconto, 2001).

The consequences of the failure of these regulating services can be significant. In Pakistan, flows of both freshwater and sediment to the Indus River Delta have been very significantly impacted over recent decades by upstream irrigation and water infrastructure development. The consequences of these reduced freshwater and sediment flows have been rapid declines in the environment of the delta, including saline intrusion into deltaic land and aquifers, and impacts on delta fisheries and mangroves (World Bank, 2005). As this area is home to a very large community, the human and environmental consequences of the loss of these services have been profound.

As with the Indus, the ongoing management challenges of the Yellow River have been well-recorded. Among these challenges has been increased flood risk in the lower Yellow River basin as a result of increased sedimentation driven by increased erosion in the basin and reduced scouring due to a reduction in peak flow levels in the river (Giordano, 2004). The management of the Yellow River indicates the challenges presented in seeking to maintain key regulating functions in large river basins.

Freshwater systems also provide important regulating services to estuarine, deltaic, and near-shore environments. Maintenance of key elements of the flow of freshwater is often important to the maintenance of ecosystems such as mangroves and estuarine fisheries, which in turn provide very significant development benefits. For example, the role of healthy mangrove forests in reducing flood risk is being increasingly recognized. To provide one instance of the importance of these estuarine systems, some 80 percent of Tanzania's prawn harvest is currently derived from the Rufiji River Delta. This fishery is of particular economic importance, as it is both lucrative and a major source of foreign exchange. Timber from the mangrove forests is an asset of considerable economic significance. Over 150,000 people inhabit the Rufiji delta and floodplain, and the majority of them rely on the resources of the wetland ecosystems for their livelihoods (Hirji et al., 2002).

Cultural Services

Freshwater systems are associated with some of the most important cultural services provided by ecosystems around the world. For many communities, rivers have a deep sacred or cultural value. This is perhaps most vividly illustrated by the River Ganga, in northern India, worshipped as a sacred river by millions of Hindus. The scale of this can be illustrated by the Kumbh Mela festival, held on the banks of the Ganga once every 12 years. These gatherings attract over 50 million people and are believed to the largest gatherings of people that have ever occurred. Many rivers provide significant amenity and recreational values to local communities.

1.2 CHALLENGES AND BARRIERS TO SUSTAINABLE FRESHWATER MANAGEMENT

The decline in the health of freshwater ecosystems around much of the planet, and the associated reduction in ecosystems services, has been widely reported. Comprehensive global data sets that provide a systematic and comprehensive record of the health and status of freshwater ecosystems are unavailable. However, based on available data sets, global surveys have identified freshwater ecosystems as suffering from greater alteration and degradation than any other ecosystem on the planet. Hence, the 2005 Millennium Ecosystem Assessment concluded:

> Inland water habitats and species are in worse condition than those of forest, grassland or coastal systems … It is well established that for many ecosystem services, the capacity of inland water systems to produce these services is in decline and is as bad or worse than that of other systems … The species biodiversity of inland water is among the most threatened of all ecosystems, and in many parts of the world is in continuing and accelerating decline. (Millennium Assessment, 2005)

These conclusions have been reflected in the recent ***Global Biodiversity Outlook 3***, published by the Convention on Biological Diversity. This concluded:

> Rivers and their floodplains, lakes and wetlands have undergone more dramatic changes than any other type of ecosystem. (Secretariat of the Convention on Biological Diversity, 2010)

The drivers of this decline are multiple, reflecting the range of uses to which freshwater systems are put. ***Global Biodiversity Outlook 3*** concurred with many other global studies to conclude that the principal drivers of freshwater biodiversity decline included abstraction of water for irrigation, industrial, and household use; the input of nutrients and other pollutants into freshwater systems; the damming of rivers for hydropower, storage, and flood control purposes; and the modification and drainage of freshwater habitats and wetlands.

In recognition of the importance of freshwater ecosystems and the services that they provide, environmental sustainability is recognized as a core principle of integrated water resources management, enshrined in the first of the Dublin Principles, which recognizes that "effective management of water resources demands a holistic approach, linking social and economic development with protection of natural ecosystems." This increasing recognition has led to the significant development of tools and approaches that seek to ensure the maintenance, protection, and restoration of ecosystems and ecosystem services in ongoing water resources management efforts.

Examples of these efforts can be given from around the world. These include major and groundbreaking pieces of legislation that seek to give effect to the core principles of IWRM, placing water resources management at the core of water planning and decision making. Among the highest-profile pieces of legislation that attempt a comprehensive approach to freshwater sustainability are the European Union's Water Framework Directive (2000) and the South African National Water Act (1998). Alongside these comprehensive efforts, a range of sectoral policy and regulatory interventions aimed at improved environmental sustainability have been developed, including a very significant global increase in interest in policies to protect and restore environmental flows (Hirji and Davis, 2009a). Major developing countries are now looking to recognize environmental flows in their water resources management policy; the recently gazetted National Ganga River Basin Authority in India has as one of its objectives the "maintenance of minimum ecological flows in the River Ganga, with the aim of ensuring water quality and environmentally sustainable development" (MOEF, 2009); similarly, the Chinese Ministry of Water Resources is currently drawing up national environmental flow standards (Speed, 2010). Important initiatives on environmental flow policy are also at various stages of development and implementation in other developing countries around the world, including Central and Latin American nations, East Africa and southern African countries, and countries in Southeast Asia.

Despite these efforts, there remain very significant barriers to the achievement of sustainable management of freshwater resources. Increasing demand for irrigated agriculture, energy, and water for industrial and domestic purposes provides a context in which pressure on sustainable management of freshwater ecosystems will be increasing. Key institutional challenges include institutional fragmentation and competing mandates in the water sector, an inadequate information base, inadequate technical and administrative capacities, corruption and governance challenges, outdated or weak policy and regulatory frameworks, and a lack of recognition of the role and function of ecosystem services.

2. CLIMATE CHANGE AND FRESHWATER ECOSYSTEMS

Climate-sustainable freshwater management is critical for economic development in both developed and developing countries (World Bank, 2010b). However, under current projections, virtually all freshwater ecosystems will face ecologically significant climate change impacts by the middle of this century, most of which will be detrimental from the perspective of existing freshwater ecosystems and the human livelihoods and communities that depend upon them. There will be few if any "untouched" ecosystems, and many water bodies are likely to be profoundly transformed in key ecological characteristics because of changes in drivers such as flow regime, thermal stratification patterns, and the propensity to cycle between oligotrophic (nutrient poor) and eutrophic (nutrient-rich and typically algae-dominated) states. This chapter builds on existing reviews to provide an outline of how climate change will alter freshwater ecosystems (Rosenzweig, Casassa, Karoly, 2007; Fischlin et al., 2007; CCSP, 2009; EA, 2005; Hansen, Biringer, and Hoffman, 2003; Poff, Brinson, and Day, 2002; Wrona, et al., 2006).

2.1 A CHANGING FRESHWATER CLIMATE

Discussions of the impacts of climate change typically focus on rising mean air temperatures and the impacts associated with these. However, in the freshwater context, the impacts of climate change on freshwater ecosystems will be manifest through a variety of variables. The key variables are discussed below.

Temperature. Air temperatures are projected to increase in the 21st century, with geographical patterns similar to those observed over the last few decades. Warming is expected to be greatest over land and at the highest northern latitudes, and least over the southern oceans and parts of the North Atlantic. It is very likely that hot extremes and heat waves will continue to become more frequent. The ratio between rain and snow is likely to change to more liquid precipitation due to increased temperatures. Changes in water temperatures are more difficult to predict. Generally speaking, surface water systems with a large surface-to-volume ratio will tend to track local/regional air temperature trends, but many qualities of particular ecosystems (and types of ecosystems) can modify this trend. For instance, changes in the date of ice breakup for large lakes can lead to shifts in the timing and number of thermal stratification events (i.e., the seasonal mixing of warm and cold layers). In some regions, water temperatures have been rising more rapidly than have air temperatures. On the other hand, in regions where there is greater snowmelt, water temperatures for some ecosystems may actually decline while air temperatures increase.

Precipitation. Precipitation is projected to increase globally. However, this is expected to vary geographically and temporally. Increases in the amount of precipitation are likely at high latitudes. At low latitudes, both regional increases and decreases in precipitation over land areas are likely. Drought-affected areas will probably increase in extent, and extreme precipitation events are likely to increase in frequency and intensity. In many places there will be changes in the timing of precipitation even if mean annual precipitation remains relatively constant.

Evapotranspiration and sublimation. Potential evaporation (a physical change of state from liquid water to water vapor) is controlled by atmospheric humidity, net radiation, wind speed, and temperature, and is predicted to increase almost everywhere under global warming. Actual evaporation is also predicted to increase over open water, following the predicted patterns of surface warming. Changes in evapotranspiration over land are somewhat more difficult to predict because of competing effects of increased carbon dioxide levels on plant water loss. Additionally, the amount and/or rate of sublimation (the physical change of state from frozen water directly to water vapor) of seasonal snowpack and glaciers appears to also be increasing, which means that this water is "lost" to the basin and passes directly to the atmosphere without entering freshwater ecosystems.

Runoff. Changes in precipitation and evapotranspiration will combine to change runoff. Runoff is likely to increase at higher latitudes and in some wet tropics, including East and Southeast Asia, and decrease over much of the mid-latitudes and dry tropics, including many areas that are presently water stressed. Water volume stored in glaciers and snowpack is likely to decline, resulting in decreases in summer and autumn flows in affected areas. Some changes can already be seen. Changes in the ***seasonality*** of runoff are widely observed. For instance, in most mountainous regions, there is less frozen precipitation falling, more rain, and lower amounts of snowpack accumulation in winter, along with accelerated spring melting. Globally, even in non-mountainous regions, the seasonal timing of precipitation is changing.

Sea level. Conservatively, global mean sea level is expected to rise by 0.18 m to 0.59 m by the end of the 21st century, due to thermal expansion of the oceans and melting of glaciers and ice-caps. Coastal and estuarine regions are also likely to be affected by larger extreme wave events and tropical storm surges.

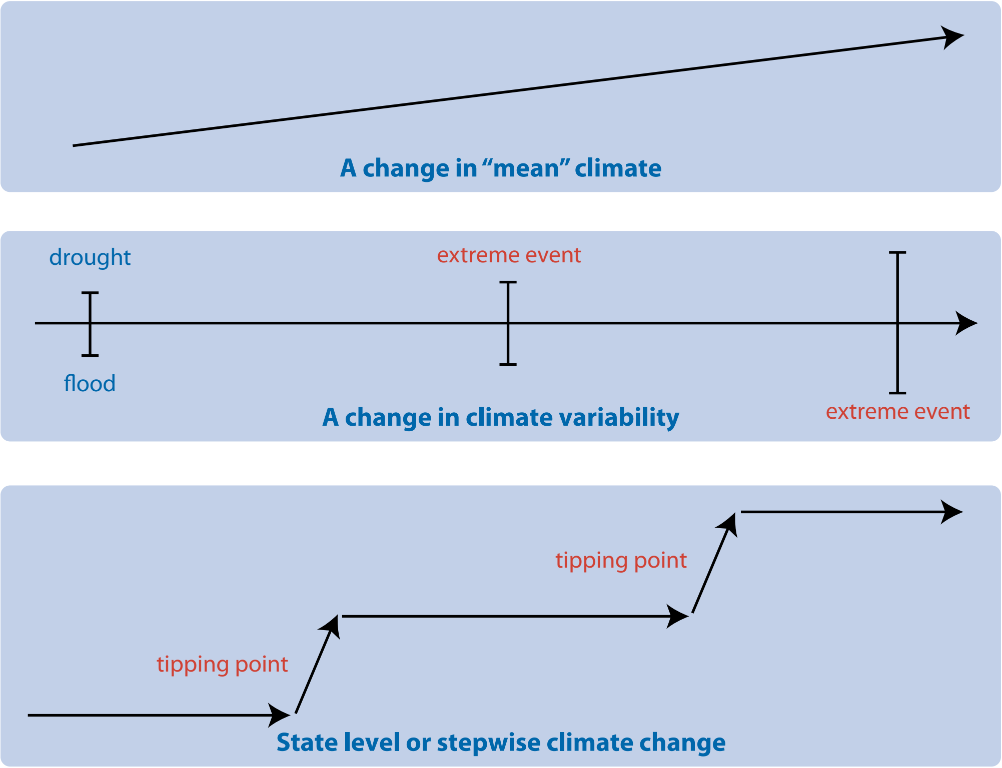
For these physical variables, change may occur via one of three trajectories (see figure 2.1):

A gradual change in "mean" climate. Variables such as air temperature, mean precipitation, or even mean monthly extreme precipitation may shift in a relatively even way in some regions. Most climate models have a bias toward depicting climate change as a gradual shift in mean variables. However, this is perhaps likely to be the least characteristic way in which climate change will be manifest for freshwater ecosystems.

Changes in the degree of climate variability around some mean value. In contrast to a shift in the mean value of some climate variable, the frequency and degree of extreme weather events are shifting in most regions. From a freshwater perspective, this often results in both more droughts and more floods, often with longer duration and greater severity (or intensity). For ecosystems, species, and people, this type of climate change is probably far more significant than changes in mean climate, even when both types of changes are occurring simultaneously. Most climate models are not able to predict with confidence changes in climate variability.

"State-level" or "modal" change in climate. State-level change is the shift of climate from a period of relative climatic stability, followed by a period of rapid shifts in many climate variables (passing a climate tipping point or "threshold"), followed by another period of relative stability. Ecosystems that depend on climate can also exhibit these types of behaviour. Examples of this type of modal change include the rapid disappearance of glaciers in Glacier National Park (glacier to snowpack to tundra to grasslands and forest); the sudden initiation, cessation, or spatial shifting of ocean currents; and major shifts in cyclical timing of global climate engines such as El Niño or the North Atlantic oscillation. On even larger scales, many major glacial-interglacial transitions occupied only a few

Figure 2.1: Three trajectories for climate change. Of these three, a change in "mean" climate is the focus of most climate models but is likely to be the least common.



decades. Modal change is extremely difficult to model and predict, though the paleoclimatic record shows many instances of stability-transition-stability climate shifts. Examples of modal change are likely to be the contexts in which ecological and economic shocks are triggered.

2.2 ECOSYSTEM IMPACTS OF CLIMATE CHANGE

The responses of freshwater ecosystems to a changing climate can be described in terms of three different but interrelated components: water quantity or volume, water timing and water quality. A change in one of these components often leads to shifts in the others as well.

Water quantity refers to the water volume of a given ecosystem, which is controlled through the balance of inflows (precipitation, runoff, groundwater seepage) and outflows (water abstractions, evapotranspiration, natural outflows). The most striking changes in water quantity may well occur through precipitation extremes leading to floods and droughts; lake and wetland levels can also change radically as a result of even slight changes in the balance between precipitation and evaporation rates. The occurrence of extreme precipitation events is expected to continue to increase globally, as is the severity of extreme events themselves. Changes in water quantity are likely to have impacts on freshwater ecosystems, on occasion through increased flooding but more often through an increase in water stress.

Water timing or water seasonality (also described as hydropattern, hydroperiod, or flow regime) is the variation in water quantity over some period of time, usually reported as a single year. Ecologists describe freshwater flow regimes as the primary determinant of freshwater ecosystem function and for the species within and dependent on freshwater ecosystems. This has been recognized in World Bank operational approaches to freshwater:

> During recent decades, scientists have amassed considerable evidence that a river's flow regime — its variable pattern of high and low flows throughout the year, as well as variation across many years — exerts great influence on river ecosystems. Each component of a flow regime — ranging from low flows to floods — plays an important role in shaping a river ecosystem. Due to the strong influence of a flow regime on the other key environmental factors (water chemistry, physical habitat, biological composition, and interactions), river scientists refer to the flow regime as a "master variable." (Krchnak et al., 2009)

The flow regime effectively acts like a clock for species and ecosystems (Poff 1997), and changing the timing of the clock has profound ecological consequences. Indeed, many freshwater conservation biologists now recommend that these ecosystems be managed for variability (Poff, 2010). This is because many terrestrial and virtually all aquatic species are sensitive to water timing. The behavior, physiology, and developmental processes of most aquatic organisms are adapted to particular water timing regimes, such as fish spawning during spring floods or accelerated metamorphosis from tadpole to adult frog in a rapidly drying wetland. Shifts in flow patterns mean that there may be detrimental mismatches between behavior and the aquatic habitat. In turn, these shifts can affect important ecosystem services such as provision of sufficient fish stock for capture fisheries.

Water quality refers to how appropriate a particular ecosystem's water is for some "use," whether biological or economic. Many fish species, for instance, have narrow habitat quality preferences for dissolved oxygen, water temperature, dissolved sediment, and pH.

Table 2.1 summarizes the range of impacts from climate change that are likely to affect freshwater ecosystems. The key "eco-hydrological" impacts mediate between changes in the physical climate and impacts on freshwater ecosystems. The range of impacts that a changing climate is likely to have on freshwater ecosystems is therefore broad and will depend on the particular context. Given the importance of flow timing, it is likely that changes to patterns of freshwater flows will be the most significant and most pervasive of these impacts. The most significant climate-induced risk to ecosystems to emerge from the case studies prepared for this report was the impact of low flows and altered hydrological conditions, especially flow regime. It is important to note that climate-driven low-flow impacts can increase even in the context of consistent annual average precipitation as a result of increased variability in annual precipitation, as a result of increased seasonality and shifts in water timing, as a result of reduced groundwater recharge resulting from more intense rainfall events, and as a result of increased evapotranspiration and greater demand for water.

As outlined in section 2.1, climate change impacts can be broadly classified as falling into two categories: shifts in climate variability (e.g., drought and flood frequency/severity) and shifts in mean climate (e.g., the precipitation

Table 2.1: Key eco-hydrological impacts of climate change on ecosystems and species

Impacts of climate change	Eco-hydrological impacts	Impacts for ecosystems and species
Changes in volume and timing of precipitation Increased evapotranspiration Shift from snow to rain, and/or earlier snowpack melt Reduced groundwater recharge Increase in the variability and timing of monsoon Increased demand for water in response to higher temperatures and climate mitigation responses	**1. Increased low-flow episodes and water stress**	Reduced habitat availability Increased temperature and pollution levels Impacts on flow-dependent species Impacts on estuarine ecosystems
Shift from snow to rain, and/or earlier snowpack melt Changes in precipitation timing Increase in the variability and timing of annual monsoon	**2. Shifts in timing of floods and freshwater pulses**	Impacts on spawning and emergence cues for critical behaviors Impacts on key hydrology-based life-cycle stages (e.g., migration, wetland and lake flooding)
Increased temperatures Reduced precipitation and runoff	**3. Increased evaporative losses from shallower water bodies**	Permanent water bodies become temporary/ephemeral, changing mix of species (e.g., from fish-dominated to fairy shrimp–dominated)
Increased precipitation and runoff More intense rainfall events	**4. Higher and more frequent storm flows**	Floods remove riparian and bottom-dwelling organisms Changes in structure of available habitat cause range shifts and wider floodplains Less shading from near-channel vegetation leads to extreme shallow water temperatures
Changes in air temperature and seasonality Changes in the ice breakup dates of lakes	**5. Shifts in the seasonality and frequency of thermal stratification (i.e., normal seasonal mixing of cold and warm layers) in lakes and wetlands**	Species requiring cold-water layers lose habitat Thermal refuges disappear More frequent algal-dominated eutrophic periods from disturbances of sediment; warmer water Species acclimated to historical hydroperiod and stratification cycle are disrupted, may need to shift ranges in response
Reduced precipitation and runoff Higher storm surges from tropical storms Sea-level rise	**6. Saltwater encroachment in coastal, deltaic, and low-lying ecosystems**	Increased mortality of saline-intolerant species and ecosystems Salinity levels will alter coastal habitats for many species in estuaries and up to 100 km inland
Increase in intensity and frequency of extreme precipitation events	**7. More intense runoff, leading to increased sediment and pollution loads**	Increase of algal-dominated eutrophic periods during droughts Raised physiological and genetic threats from old industrial pollutants such as dioxins
Changes in air temperature Increased variability in temperature	**8. Hot or cold-water conditions and shifts in concentration of dissolved oxygen**	Direct physiological thermal stress on species More frequent eutrophic periods during warm seasons Oxygen starvation for gill-breathing organisms Miscues for critical behaviors such as migration and breeding

regime changes in seasonality, as when spring rains arrive a month earlier, or less winter precipitation falls as snow). Many regions globally are seeing increases in climate variability, but the seasonality of precipitation and evapotranspiration regimes is changing universally, even in the absence of changes in the mean annual precipitation (IPCC, 2007; IPCC, 2008). Because changes in water timing result in changes in water quantity and quality, shifts in the timing of freshwater flows have become a leading driver in global declines in freshwater biodiversity as a result of a range of anthropogenic impacts. As the pace of climate change quickens, this pressure is likely to accelerate.

2.3 SENSITIVITY: RISK AND HOT SPOTS

The literature describing the threats to water and freshwater ecosystems is large and growing rapidly; the tone is often dire and alarmist, with widespread predictions of a global water crisis. Perhaps as a result of the unfortunate term "global warming," such a crisis is frequently framed as increasing water scarcity. These views are not represented in either the observed or projected data as reported in IPCC reports (e.g., Bates et al., 2008). The IPCC has concluded that globally the hydrological cycle is intensifying, which means that the atmosphere holds ***more*** water vapor than in recent decades, and global precipitation volume appears to be increasing.

However, this does not mean that all places are receiving more precipitation relative to the pre-industrial era or even that regions that are receiving more precipitation actually have greater runoff (and higher flows). The effects of climate change are not evenly distributed globally or across a particular landscape or a basin, and certainly not in regard to such aspects of climate as precipitation and evapotranspiration, projections of which are considered highly uncertain and low confidence at the regional and local scales (Bates et al., 2008). Similarly, in temperate, tropical, and subtropical regions fed by seasonal snowpack, there are worrying reports that while wet-season precipitation is growing, accumulated snow may be sublimating (i.e., becoming water vapor rather than melting and entering the surface or groundwater cycle as liquid water) more often, resulting in lower dry-season flows. Within this report's case studies, we see trends in several climate variables, such as increasing precipitation (Tocantins, Siphandone–Stung Treng), lengthening dry periods (Okavango, Breede), and more frequent and severe extreme weather events (all cases). However, these studies describe local events and cannot be used to generalize regional or global trends. What we can be certain of is that water timing has already changed in most regions as a result of climate change, and the rate and degree of these changes will be accelerating in coming decades.

As a result, by focusing on how water timing is shifting, we can contextualize how "normal" quantity and quality are changing in a manner that is relevant to ecosystems, biodiversity, and livelihoods. Accordingly, one can visualize a tapestry of risks across a freshwater landscape (described at the basin or catchment level), with particular risks manifesting at different points in time and space. For example, smaller and low-volume headwater streams are more likely to be vulnerable to low-flow impacts than are larger, high-volume, and main stems of river systems.

Equally, the variability of hydrological systems means climate risks will also be uneven in time, both inter- and intra-annually. Systems may be at risk for only a short period of the year; for example, during the dry season when river systems may already be vulnerable to water stress. Intra-annual variability may also mean that systems remain unstressed for a number of years but then experience a damaging, climate-driven drought. Thus, key vulnerabilities to climate change may occur for just a few weeks or months in a decade. It is important to identify these time- and space-bounded risks when designing adaptation responses.

It is also important to understand the determinants of sensitivity and vulnerability in freshwater ecosystems when designing adaptation responses. Sensitivity describes the characteristics of a freshwater ecological system that make it sensitive to changes in the environment. These changes may be in terms of water quantity, quality, timing, or a combination of the three. Not all ecosystems will be equally sensitive, with some freshwater ecosystems and species better able to withstand climate shifts than others.

Given that changes to the volume and timing of flows are likely to be the most profound impacts of climate change on freshwater ecosystems, freshwater systems that already experience threats to their flow patterns on a regular basis are likely to be the most sensitive to climate change. Thus, the ephemeral pans and rivers of the Boteti in Botswana are likely to be highly vulnerable to climate change, as the ecosystem is very sensitive to changes in rainfall and the area is likely to experience significant drying in the future. Importantly, this sensitivity may not be a function of total annual water stress across the basin but of seasonal vulnerability to water stress. For similar reasons, systems with limited assimilative capacity are likely to be more sensitive to climate changes, particularly systems already experiencing considerable stress from non-climate pressures.

Box 2.1: Potential impacts of shifts in water timing on the Himalayan Mahseer

The Himalayan, or golden, mahseer (***Tor putitora*** Hamilton) is a fish that is endemic to about 25 major Himalayan rivers and a few (5–10) rivers in the northeast hills south of the Brahmaputra. However, only the foothill sections are inhabited by the species, restricting the effective available habitat in any river to about 50 km, although nearly 100 km of river may be used during upstream migration. The total population of ***Tor putitora*** Hamilton may thus be spread over about 3,000 km of river length, most of which is already degraded or threatened. Existing and proposed hydroelectric plants are a particular threat to habitat and connectivity. The golden mahseer provides an attractive fishery by virtue of its size.

Mahseer have to migrate ~50 km upstream into shallow, spring-fed tributaries and lay their spawn when the monsoon is in full swing and rivulets are constantly flooded. Their ascent begins with the advent of summer and melting of glaciers after February into the deeper, glacier-fed rivers. The migratory habits serve to disperse the stock, exhibiting a food resource utilization strategy. The species appears to be stenothermic (narrow range for temperature tolerance, probably 12–19°C). Migration in the context of water temperatures and the timing of runoff is thus crucial to the survival of the species.

Climate change impacts on snowfall, glacial melt, and the timing of spring snowmelt are likely to have a variety of impacts on runoff that may, in turn, impact both the migration requirements and nursery habitat of mahseer. For example, warming is likely to result in reduced snow cover and therefore lower spring flow in the snow-fed rivers. A reduction in discharge will expose riffles and endanger the connectivity of the pools, thereby causing stress to migrating individuals. Reduced turbidity, lower current velocities, and a rise in water temperature as a result of climate change will distort the familiar cues for upward migration. The decrease in current velocities will increase detritus levels and create a shift from oligotrophic to mesotrophic conditions, causing algal blooms. Dissolved oxygen content will also decline with a rise in temperature, affecting physiological processes and energy needs during migration. A disturbed ecosystem is prone to biological invasions, potentially changing the food web. These effects could result in the loss of spawning grounds and nurseries for this species.

Source: Professor Prakash Nautiyal, HNB Garhwal University, Srinagar

While there are certain characteristics that may make freshwater ecosystems sensitive to climate change impacts, there are equally some characteristics of freshwater ecosystems that confer resilience. These include the presence of a diversity of habitats within a system, providing refugia for species or ecosystems at times of climate-induced stress.

2.4 TIPPING POINTS VERSUS GRADUAL CHANGE

Some ecosystems can have tipping points that can be triggered by large-scale shifts in climate regime but can also occur following more modest shifts in climate. Many discussions of the impacts of climate change on ecosystems point to key tipping points that whole ecosystems will experience. Examples of such tipping points are the geomorphological changes in a river channel following an extreme flood, with extensive habitat destruction and system disequilibrium; the dramatic biogeochemical responses within a water body when nutrient levels exceed the eutrophic threshold and a series of algal bloom and anoxic events ensue; and the shift in a wetland from a permanent water body to an ephemeral or temporary system.

While tipping points will occur in some freshwater ecosystems, other systems will undergo slow, steady degeneration in the face of climate change. Productivity is undermined and species are gradually lost as elements of the system are stressed. For example, increased water temperatures and reduced flow levels may lead to a decrease in the quantity and diversity of invertebrate species, leading, in turn, to declines in fish populations. These gradual impacts of climate change will often be exacerbated by additional impacts from other human-induced stresses.

2.5 UNDERSTANDING FUTURE IMPACTS: CAVEAT EMPTOR

As conceded by the IPCC FAR, the ***documented*** evidence base for climate impacts on tropical regions and the Southern Hemisphere is sparse. The evidence is even more limited when the search is focused on freshwater ecosystems. The lack of documentation does not imply that effects are not widespread or significant for species

Box 2.2: Salmonids: The fruit of extensive climate impact research

A series of environmental trends across western North America has been identified that has direct relevance to many aspects of salmonid habitat. These trends include warmer and more variable air temperatures (Sheppard et al., 2002; Abatzoglou and Redmond, 2007), increasing precipitation variability (Knowles et al., 2006), decreasing snowpack volume, earlier snowmelt (Hamlet et al., 2005; Mote et al., 2005), and increasing wildfire activity (Westerling et al., 2006; Morgan et al., 2008). The timing of peak spring runoff has advanced from several days to weeks across most of western North America (Barnett et al., 2008). Less snow and earlier runoff reduce aquifer recharge, reducing baseflow contributions to streams in summer (Stewart et al., 2005; Luce and Holden, in review; Rood et al., 2008). Inter-annual variation in stream flow is increasing, as is the persistence of extreme conditions across years (McCabe et al., 2004; Pagano and Garen, 2005). In many areas of western North America, flood risks have increased in association with warmer temperatures during the 20th century (Hamlet and Lettenmaier, 2007). Streams with midwinter temperatures near freezing have proven especially sensitive to increased flooding because of their transitional hydrologies (mixtures of rainfall and snowmelt) and the occasional propensity for rain-on-snow events to rapidly melt winter snowpacks and generate large floods (Hamlet and Lettenmaier, 2007). Stream temperatures in many areas are increasing (Peterson and Kitchell, 2001; Morrison et al., 2002; Bartholow, 2005) due to both air temperature increases and summer flow reductions, which make streams more responsive to warmer air temperatures.

These complex, climate-induced effects are shifting habitat distributions for salmonids, sometimes unpredictably, in both time and space. A warming climate will gradually increase the quality and extent of habitat into regions that are currently unsuitable for some salmonid species because of cold temperatures (e.g., at the highest elevations and northern distributional extents; Nakano et al., 1996; Coleman and Fausch, 2007). Previously constrained populations are expected to expand into these new habitats. Some evidence suggests this may already be happening in Alaska, where recently de-glaciated streams are being colonized by emigrants from nearby salmon and char populations (Milner et al., 2000). On the other hand, human-induced warming will render previously suitable habitats unsuitable. At the same time, reduced summer flow will decrease available living space within individual stream reaches and may also reduce productivity, growth, and survival by decreasing positive interactions with surrounding terrestrial ecosystems (Baxter et al., 2005; Harvey et al., 2006; Berger and Gresswell, 2009; McCarthy et al., 2009). Some upstream tributaries could switch from perennial to intermittent flow, eliminating salmonid habitats entirely (e.g., Schindler et al., 1996). In the remaining permanent streams, increasing variability in drought and flood cycles may also decrease the likelihood of salmonid population persistence or begin to favor some species over others (Seegrist and Gard, 1972; Beechie et al., 2006; Warren et al., 2009).

Despite a relative wealth of knowledge regarding salmonid fishes, case histories documenting long-term responses either in habitat conditions or at the population level are relatively rare. Juanes et al. (2004) documented advances in initial and median migration dates of 0.5 day per year over a 23-year period for Atlantic salmon along the East Coast of North America. Hari and colleagues (2006) linked long-term warming trends in stream temperatures across Switzerland to outbreaks of fish diseases in thermally marginal areas and upstream shifts in brown trout populations. Isaak and colleagues (in review) assessed water temperature trends across a large river network in central Idaho and found summer temperature means to be increasing at the rate of 0.27°C per decade, which was eliminating habitat for the native char species at a rate of 0.9 to 1.6 percent per year.

However, most assessments linking salmonids and climate change are based on model predictions of future conditions. For example, Rieman et al. (2007) estimated that a 1.6°C temperature increase across the southern extent of the bull trout range in western North America would eliminate approximately 50 percent of currently suitable thermal habitat. The analysis highlighted considerable spatial variation in habitat losses, with the coldest, steepest, and highest-elevation mountains projected to lose a smaller proportion of habitat than warmer and less-steep areas. In a similar assessment for nearby populations of Chinook salmon, however, the highest-elevation habitats were projected to be most sensitive as hydrologies shifted from snowmelt to rainfall runoff, and lower-elevation habitats appeared to offer the best conservation opportunities (Batten et al., 2007).

and ecosystems. A lack of meteorological data hampers both predictions of impacts on freshwater ecosystems and the management of water resources for humans. Mid- and low-latitude regions have suffered a demise of monitoring networks since the 1980s that has been long recognized (WMO, 2005). Without reliable records of river flow, evaporation, groundwater levels, and water quality, it is difficult to interpret past change in freshwater ecosystems. In addition, detailed information on freshwater biota is available for only a few taxonomic groups — and often for only a few families, genera, or species in those groups (Heino, Virkkala, and Toivonen, 2009). Even where data exist, national security or competing interests between agencies can restrict access.

There have been attempts to model the impacts of climate change on ecosystems. Because of the data limitations, these models are not definitive but can give guidance on where impacts may be likely to occur. Although there is strong consensus among climate models about future air temperatures, predicted patterns of rainfall and runoff are far less certain, especially for developing regions (figure 2.2). Even for annual average precipitation, about half the regions shown have inconsistent predictions as to whether future precipitation and runoff will increase or decrease. This lack of consensus reflects a weak understanding of fundamental climate controls in many regions, leading to different interpretations of land-atmosphere processes and model outputs. For example, when these models are applied to past events such as the abrupt drying across the Sahel in the late 1960s to "test" model validity, contradictory model "explanations" — including rising greenhouse gas concentrations, vegetation changes, natural climate variability, and interactions between these variables — are revealed. This uncertainty increases as predictions are made for more distant time periods and for smaller spatial scales.

The common practice of providing average results from "ensembles" of models can be highly misleading. The results may be biased by strong outliers, and the practice can also misrepresent differences and disagreements between models. It is particularly difficult to assess ecosystem impacts using these modeled outputs because the majority of studies focus on gradual shifts in either the mean or seasonality of climate and associated impacts. Relatively little information is available on changes in (precipitation) extremes, variability, or abrupt transitions at the scales required for adaptation and development planning (Wilby et al., 2009). However, it is precisely these changes that may have the most profound impacts for freshwater ecosystems. Climate model projections for evapotranspiration, humidity, and indirect and synergistic impacts are even more tenuous than for precipitation. Thus, even where the models agree, there is insufficient detail for high-confidence quantitative water resource planning at the river basin scale — even large river basins such as the Mississippi in North America or the Yangtze in China.

In addition, climate models on their own are insufficient to provide details of impacts on ecosystems. This requires that the outputs of climate models be fed into typically complex

Figure 2.2: Changes in precipitation for the period 2090–2099 relative to 1980–1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66 percent of the models agree in the sign of the change, and stippled areas are where more than 90 percent of the models agree in the sign of the change (IPCC 2007).

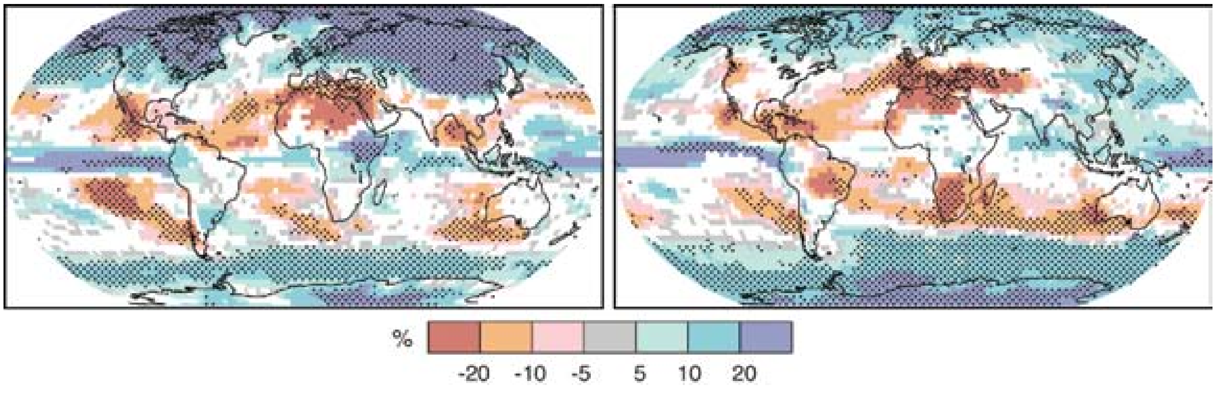
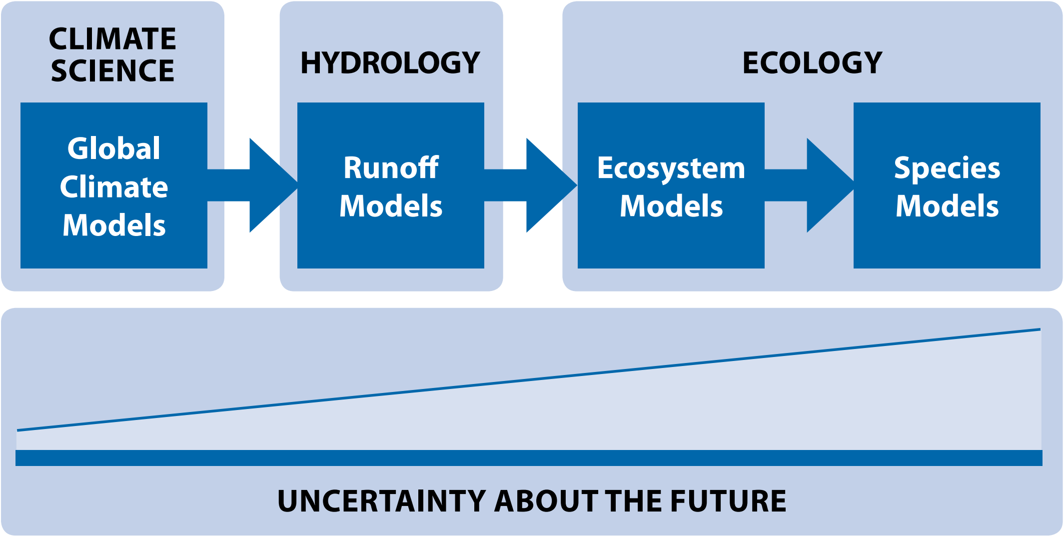


Figure 2.3: Uncertainty about the future increases as results from uncertain models are combined. *Climate Change 2007: Synthesis Report*. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 3.3. IPCC, Geneva, Switzerland..



hydrological models and then into ecological models. There are clear dangers to the amplification of initial climate model errors.

Undoubtedly, climate models will improve, but climate science faces significant modeling challenges. For the foreseeable future, it would be unwise to base complex ecosystem adaptation responses on deterministic climate models. Nevertheless, decisions cannot be put off because of this uncertainty. This implies that, as discussed in chapter 3, the assessment of ecosystem vulnerability should be based on risk assessment rather than on deterministic modeling (Matthews and Wickel, 2009; Matthews, Aldous, and Wickel, 2009).

Despite this caution, climate models remain suitable for highlighting broad ***qualitative*** trends in hydrological behavior. For example, higher air temperatures mean that more winter precipitation falls as rain rather than snow, and that the onset of spring snowmelt is earlier (and sometimes more rapid). Hence the Andes, Tibetan plateau, much of North America, Scandinavia, and the European Alps are expected to see increased seasonality of flows with higher spring peaks and lower summer flows. Other robust predictions include higher flows in rivers fed by melting snowpacks and glaciers over the next few decades, followed by reductions once these stores have wasted (Barnett, Adams, and Lettenmaier, 2005). Likewise, warmer temperatures will favor more evaporation and drying of

Box 2.3: Impacts and physiology: bioclimate envelope and ecosystem modeling

The ability to model the macro-scale impacts of climate change has improved because of habitat- and species-specific bioclimatic envelope and mechanistic vegetation modeling (Scholtze et al., 2006). Bioclimatic models combine information about suitable "climate space" and dispersal capability (based on species' traits) to predict the ecological consequences of different climate scenarios. For example, recent work has highlighted the vulnerability of Europe's small and isolated network of Natura 2000 wetland ecosystems and in particular the potential for range contractions in amphibians, a group closely associated with freshwater ecosystems (Voss et al., 2008; Araujo, Thuiller, and Pearson, 2006). Although potentially useful for predicting the spread of exotic invasive species (e.g., zebra mussels), these models neglect or overemphasize particular determinants of species' distributions, such as population dynamics, interspecies interactions, or the direct physiological effects of increased carbon dioxide concentrations. So far there have been very few (if any) bioclimatic studies in developing regions except for global analyses of extinction risk (Pounds et al., 2006). For freshwater ecosystems, this approach typically combines eco-hydrological models with climate scenarios and is applied to commercially important fish species. In most cases they should not be applied in a deterministic fashion. At best, they provide some qualitative estimate of simplistic, species-level responses to small shifts in climate variables.

soils, increasing the risk of drought and depleted runoff, as is anticipated for the margins of the Mediterranean basin.

2.6 CLIMATE CHANGE AND OTHER HUMAN PRESSURES

In the majority of cases, damage to freshwater ecosystems will occur as a result of the synergistic impacts of climate change with other anthropogenic pressures arising from population and economic growth or land-use change. In many cases, climate will not be the predominant driver of freshwater biodiversity loss over the next half century. This conclusion was reinforced by the case studies undertaken for this report. In all cases where climate impacts were identified as a risk, this was as a consequence of symbiotic effects with other human pressures. In the case of the Tocantins-Araguaia River basin in Brazil, the case study concluded clearly that climate change was likely to have a far less significant impact on ecosystems in the foreseeable future than other human pressures (WWF, at press). It is imperative, therefore, that climate impacts be understood as part of the broader set of pressures impacting freshwater systems.

Box 2.4: Compounding pressures: water scarcity and agriculture

At river basin scales, projected rates of population and economic growth are expected to be much stronger determinants of local water scarcity than is climate change (Arnell, 2004). The International Water Management Institute (2007) estimates that the water requirements for agriculture could double by 2050, before considerations of climate change have been factored in. This implies that even under static climate conditions there will have to be trade-offs between water used for local food production and water required to sustain aquatic ecosystems. This situation is illustrated in the Breede system in the Western Cape, South Africa. The Breede estuary is one of the most important and productive estuarine fisheries in South Africa but has been affected by low inflows due to upstream abstraction for agriculture. The water futures identified for the basin threaten to exacerbate this impact due to drying climate conditions. Increased irrigated agriculture has been identified as an important growth strategy. Such a scenario would lead to saline intrusion, siltation of the river mouth, and temperature impacts in the estuary (WWF, at press).

There are many examples of these synergistic effects:

- The accidental transfer of an aquatic exotic species to a freshwater ecosystem that is warming and more suitable to the invasive could fuel a rapid decline in ecosystem quality for the preexisting native species.
- Higher volumes of groundwater abstraction associated with coastal zone development will hasten ingress of saltwater to shallow aquifers that are also at risk from rising sea levels.
- The impact of increased freshwater temperatures will lead to increased risks of eutrophication, driven by raised levels of nutrient enrichment by human activities.
- Changes to land use will increase the flood and pollution impacts of more intense rainfall events under climate change.

Clearly, systems with fewer such traditional stresses will be more inherently resilient and capable of adapting on their own. Human impacts thus remain a critical focus of sound, sustainable resource management in an era of a shifting climate. However, focusing on only these traditional pressures is not enough. Vulnerability assessments should be used to identify additional pressures arising from climate change.

Mitigation, Adaptation, and Mal-adaptation

There can be interactions between climate mitigation measures and climate adaption measures that affect aquatic ecosystems. First, changes to temperatures and precipitation are likely to lead to changes in demand for water. In irrigated agriculture, increased temperatures are likely to lead to increased evapotranspiration, increasing water demand, and decreasing runoff. At the same time, changes to either the quantity or timing of precipitation may make areas that are currently viable for dryland agriculture dependent on irrigation in the future. It is precisely in these contexts where reduced precipitation and increased temperatures are driving increased demand for irrigation that freshwater systems will already be starting to experience low-flow impacts. Increasing temperatures are also likely to drive increased demand for urban water use.

Second, some attempts to enable human societies and economies to respond to climate change may decrease the ability of ecosystems to adapt. Examples of this are likely

Box 2.5: Compounding the devastating effects of development on Lake Chad's dwindling water resources

Lake Chad, like so many of the world's closed (internally draining) basins, is experiencing extreme stress. It is a shallow lake at the edge of the Sahara desert and is economically highly important, providing water to over 20 million people in the four countries that surround it (Chad, Cameroon, Niger, and Nigeria). The Lake Chad fishery is critical for regional livelihoods.

Over 90 percent of Lake Chad's water comes from the Chari River. This river feeds low-salinity water into the lake, such that the lake has remained fresh despite very high levels of evaporation. Because the lake is very shallow, only 10 m at its deepest point, the marked evapotranspiration losses result in dramatic fluctuations in lake levels both seasonally and intra-annually. Over half of the lake's area is made up of islands, reed beds, and mud banks that provide essential habitat to breeding waterbirds and endemic fish species. Lake Chad has no outlet, with most of its water either lost to the atmosphere or feeding into aquifers in the Soro and Bodele depressions.

In recent years, the level of Lake Chad has dropped dramatically, well below levels previously recorded. Lake Chad is currently about 3 percent of its maximum size during the period 1930 to 1973, having shrunk from about 40,000 km2 40 years ago to less than 1,300 km2 today. This is primarily as a result of hydropower impoundment and over-abstraction of water from the lake and the main tributary, which have had dramatic effects on both wildlife and dependent societies. Several endemic species have disappeared, and there has been conflict between the member states regarding borders and the ownership of the dwindling water resources.

Climate change will exacerbate the unsustainable utilization of Lake Chad's freshwater resources. Increased temperatures and water loss through elevated evaporation rates will be particularly profound, given the anticipated 2–4°C temperature increase in the region over the next 50 years. In addition, there is evidence for a potential reduction in rainfall of up to 200 mm. Assuming the status quo, these climatic changes will effectively eradicate Lake Chad within a few decades, with the collapse of ecosystems occurring in advance of the actual loss of the lake's status as a permanent water body.

Widespread recognition of the dramatic implications of this scenario has resulted in the formation of the Lake Chad Basin Commission and the development of engineering responses to the problem. A proposal that is gaining momentum is the diversion of water from the Congo River into the Lake Chad basin (into the Chari River), requiring a transfer over some 100 km. As of late 2009, cooperation between the basin commissions (Lake Chad Commission and the Congo Basin Commission — CICOS) has advanced, and a feasibility study is under way to explore this option.

Source: Assessment of the vulnerability of Africa's transboundary waters to climate change, UNEP, at press.

to include new water resource infrastructure constructed in the expectation that it will assist in climate adaptation but without adequate consideration of the impacts of this infrastructure on ecosystems or their ability to adapt to climate change. This may apply to both water storage and flood defense infrastructure.

Third, many low-carbon energy sources require significant volumes of water or are likely to have significant negative impacts on freshwater ecosystems. This applies most clearly to expansion in global hydropower production, as well as to increased water demand from biofuels and carbon capture and storage (CCS) technologies.

2.7 IMPLICATIONS FOR BIODIVERSITY CONSERVATION

Until the 1970s and 1980s, biodiversity conservation prioritized species rather than ecosystems, particularly for keystone, charismatic, economically important, or highly visible species. Freshwater conservation of this era emphasized one or two endangered fish species in a given basin, for instance, with large-scale spawning facilities created to bulk up the numbers of individuals present. In recent decades, however, the focus of much conservation work has shifted onto maintaining whole ecosystems or even groups of ecosystems at a "landscape" level. This type of approach has emphasized the restoration of habitat; connectivity between segments of a particular ecosystem (or between neighboring ecosystems); and relationships between species, such as the invertebrate prey of an endangered fish. The goal has become to create a healthy, sustainable ecosystem. The shift to landscapes and ecosystems represents a major leap forward toward effective conservation.

However, climate change presents a major challenge to how we think about conservation. Climate is a major determinant of the qualities of any given freshwater ecosystem. Both a species and a landscape approach to conservation assume that conservation is essentially restoring a species or ecosystem to an earlier, more pristine state. For conservation biologists historically, the practice of conservation has been an inherently retrospective exercise. Conservation's ultimate goals have largely been unchanging preservation or sustainable, balanced use. But these goals may no longer be sufficient. Hydrological function can be restored (e.g., reconnecting segments of a river divided by infrastructure), but it may not be possible to restore past ecosystems to precisely the way they were before (Matthews and Wickel, 2009; Matthews, Aldous, and Wickel, 2009).

In effect, climate change creates a moving target for managing ecosystems and species. Conservation biologists are now struggling with the process of incorporating methodologies that are forward-looking, are robust to future climate uncertainty, and operate effectively across both landscapes and long time periods. The direction of the practice of conservation itself is extremely uncertain and is likely to require consideration of conservation objectives that are shifting and evolving to new circumstances, in addition to the restoration of systems to past states.

3. ASSESSING VULNERABILITY: METHODOLOGY AND SUMMARY CASE STUDIES

This chapter outlines the methodological approach to the assessment of freshwater ecosystem vulnerability and risk to climate change, and provides summaries of a number of case studies that were used to incrementally develop this methodology. The need for vulnerability assessments as a mechanism to support water sector decision making is increasingly being recognized as a central component of adaptation to climate change. Recommendations on the widespread use of vulnerability assessment are central to the conclusions of the Bank's *Water and Climate Change Flagship Report* (World Bank, 2009), and the recommendations made in this chapter should be read in conjunction with the discussion in that document.

Assessment of vulnerability to climate change can be undertaken within three broad contexts in World Bank and partner planning and operations:

- **Strategic Environmental Assessment (SEA) in the water sector.** The emerging use of SEA for water resource policy and planning processes and programs represents an important opportunity for the assessment of climate vulnerabilities and appropriate response strategies. As discussed in chapter 4, the strategic planning of water resources development and infrastructure will play a key role in enabling successful adaptation. In order to strengthen these efforts, an SEA that includes a substantive vulnerability and risk assessment is likely to be an important tool. This can be applied in a variety of contexts and is likely to be one of the most important contexts in which vulnerability assessment can be undertaken.

- **National adaptation or water sector policy formulation, and national or basin water resource planning processes.** In these cases, iterative vulnerability assessments can identify the most critical vulnerabilities within the country, basin, or region. The assessments can help identify adaptation pathways and measures that should be included in national or basin policy and planning. A range of Bank activities provide opportunities for the design and development of adaptation measures, including water sector reform and support packages or as part of broader regional or national adaptation and development strategies (e.g., NAPAs).

- **Project and infrastructure decision making**. The Water Anchor Flagship report also recognizes the potential of vulnerability assessments in the design of infrastructure and other water resource project lending. However, its approach to infrastructure vulnerability assessments currently does not include ecosystem vulnerability. The methodologies described here provide an opportunity to incorporate this element into the analysis.

3.1 VULNERABILITY AND CLIMATE RISK ASSESSMENT METHODOLOGIES

The overall approach to vulnerability assessment set out here addresses the key issues set out in chapter 2. It has been developed based on existing analyses in the literature, in particular the approaches set out in recent World Bank reviews (World Bank, 2009).

Overall Approach to Assessment

The assessment method set out below is scalable both temporally and geographically (and thus can be used for both national- and project-level planning) and is flexible in application, given the resources available. The same process can be used to identify risks in a matter of days at a small sub-basin scale, using expert opinion, or it can form the basis for a regional investigation based on years of original research.

It is worth making an important distinction between the concept of "impact assessment" and the concept of "vulnerability assessment." As the discussion in part 1 emphasized, consideration of future impacts of climate change cannot be based simply on downscaled climate models; instead it requires an assessment of ecosystem sensitivities and a variety of possible futures. While an impact assessment depends on predictions from downscaled modeling, a vulnerability assessment adopts a broader and more cross-sectoral view, without reliance on the accuracy of these models.

Risk-Based Approaches

Given the considerable uncertainties about the future impacts from climate change, a risk-based approach based on an understanding of system vulnerability and the drivers of risk holds more promise than does a deterministic approach. Vulnerability assessment and the design of adaptation responses should therefore be modeled on risk assessment approaches and methods. A risk-based approach to development planning has been strongly highlighted in the 2010 World Development Report, which has emphasized the importance of "robust" rather than "optimal" strategies, based on scenarios and options (World Bank, 2010b).

Risk assessment frameworks abound in the literature. Risk-based approaches typically involve (1) definition of the objectives and identification of the components of interest/concern, (2) establishment of the impact and likelihood of events that could compromise those objectives, (3) identification of the options that reduce the risk of the identified events, and (4) assessment of adaptation options to determine suitability and timing of intervention.

The World Bank's existing approach to climate change risk assessment in the water sector builds on a number of risk assessment methodologies (World Bank, 2009) and is briefly described in box 3.1.

Top-Down and Bottom-Up Assessments

The risk assessment process outlined in the Water Anchor Flagship report distinguishes between "top down," or narrative scenario–driven, and "bottom up," or threshold-focused, approaches to assessing risk. Top-down approaches attempt to characterize the likelihood of adverse impacts through the generation of models of future hydroclimatic change. Bottom-up approaches involve investigating the exposure, sensitivity, and adaptive capacity of the system of concern.

In many contexts, predictive, deterministic, and top-down methodologies have dominated thinking on adaptation to climate change. These methods involve (1) generating a formal eco-hydrological climate model, downscaled circulation model, and emissions scenario at the project or planning scale; (2) applying the scenario to an impact model; and (3) considering appropriate responses to projected impacts. But as was shown in chapter 2, high-confidence projections for precipitation, evapotranspiration, and runoff at local spatial scales that are

Box 3.1: World Bank framework for risk-based decision making for water investments

The World Bank's approach is built on three stages: (1) objective definition, (2) risk assessment, and (3) options identification and evaluation.

***Stage 1*: Identify problem, objectives, performance criteria, and rules for decision making.**

1. Define problem and objectives — identify system of interest and establish overall objectives;
2. Establish "success" or "performance" criteria and associated thresholds of tolerable risk; and
3. Identify rules for decision making that will be applied to evaluate options.

***Stage 2*: Assess risks.**

1. Identify the climate and non-climate variables that could influence potential outcomes, i.e., that the exposure unit is potentially sensitive/vulnerable to; and
2. Identify the alternative future states or circumstances that may occur (both climate and non-climate) and the impact of these on the exposure unit and performance criteria (including the relative importance of climate and non-climate drivers).

***Stage 3*: Identify and evaluate options to manage risk.**

1. Identify potential adaptation options to meet success criteria; and
2. Evaluate adaptation options according to degree of uncertainty and established rules of decision making. In all circumstances, look for no regrets, low or limited regrets, and win-win, and particularly so when there is high uncertainty. The options of "do nothing" or "delay decision" are possible. Avoid climate decision errors (over-adaptation, under-adaptation, and associated mal-adaptation).

valid for decades exist for very few regions, and these gaps may never be filled.

In order to overcome these shortcomings, scenario-driven assessments can be complemented by bottom-up assessments that seek to understand the key points of vulnerability within ecosystems and associated management systems. This not only can permit an identification of the points of potential concern but also start to highlight the areas where measures could be focused to increase systemic resilience. Such an approach is particularly applicable in the context of ecosystem vulnerability. A bottom-up analysis of where ecosystems are likely to be most sensitive to changes in climate should therefore be an integral part of vulnerability assessments.

Development and Climate Trajectories

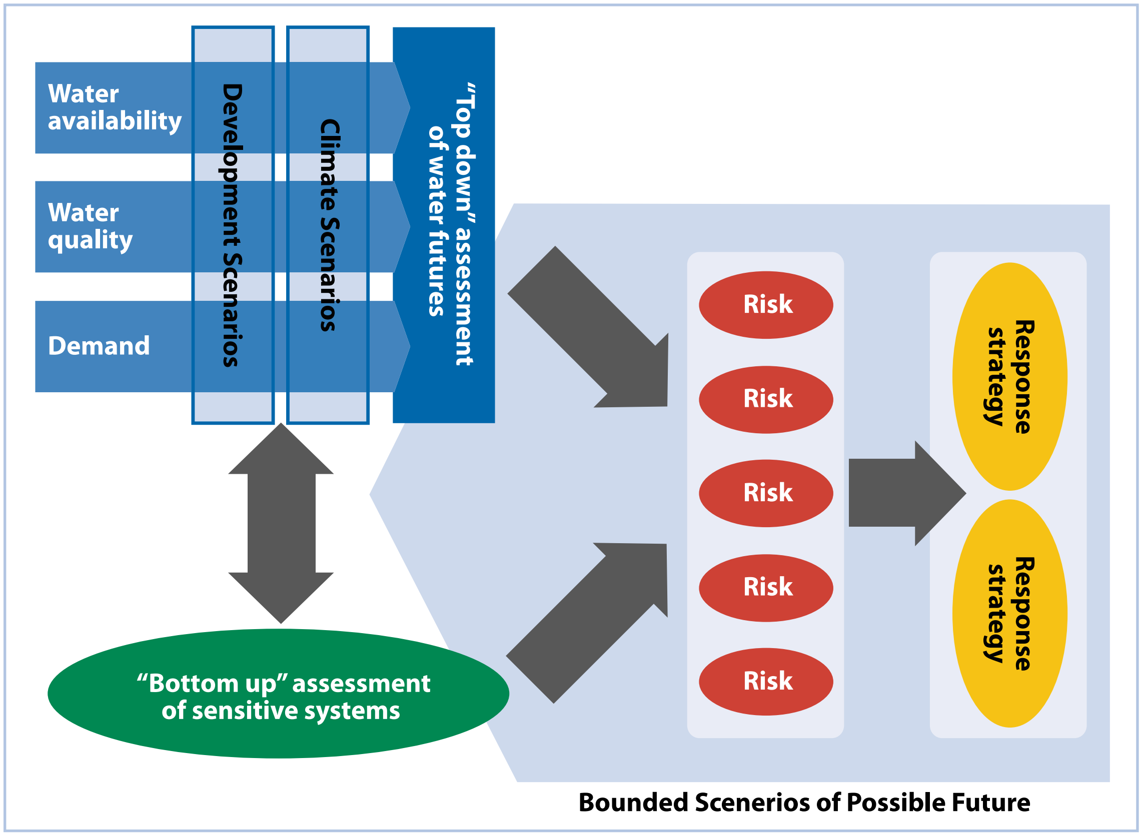
As noted in chapter 2, ecosystem decline will often result from the interplay of a number of stressors, including climate change. The other stressors are typically those associated with economic development, such as changes in land use, shifts in demography, improving socioeconomic conditions leading to increasing urban and agricultural demand for water, and unsustainable resource exploitation.

Vulnerability assessment therefore needs to consider the impacts of both climate and development trends. Like climate futures, these development futures are also characterized by considerable uncertainty, particularly in rapidly changing economies in the developing world and across the longer time horizons relevant to climate change. Accordingly, an approach built on multiple development pathways, with multiple development futures, is more appropriate than is reliance on a single deterministic development future.

Scenarios and the Emergence of Water Futures

Under this approach, a range of climate (physical) and development (socioeconomic) scenarios manifest as a range of future scenarios of water availability and demand. These future water scenarios inform the temporal and spatial scales of water quantity, quality, and timing and provide a bounded set of possibilities that can

Figure 3.1: Representation of the approach to vulnerability assessment



form the basis for the identification of risk and, therefore, adaptation strategies.

Detailed Vulnerability Assessment Methodology

The detailed methodology proposed for freshwater ecosystem vulnerability assessment (figure 3.1) follows the three stages depicted in the World Bank report.

Stage One: Defining Scope and Objectives

A number of important preparatory steps are necessary before the risk assessment can be undertaken. Defining objectives for a vulnerability assessment is central to selecting the appropriate geographic and temporal scope of analysis. Objectives and goals also inform the selection of methods and serve as the overall guide and measure by which impacts, risks, and vulnerabilities can be assessed.

Stage 1 has the following elements:

1. Overall background description of the basin, aquatic ecosystems, and associated ecosystem services and livelihoods.

2. Disaggregation of the overall basin into a number of component units. These different units will be used to assess risks in different parts of the system. Disaggregation might be based on tributaries and hydrological units; in other systems, the appropriate division may be based on ecological zones; for example, high-altitude headwaters versus mid-altitude main tributaries versus delta or estuarine areas.

3. Identification of ecosystem objectives or thresholds of concern. This can include an assessment of priority ecosystems or species of concern within the basin. Objectives can be established for ecosystem components; identified species; or ecosystems that support livelihoods, hydro-physical conditions, or socioeconomic aspects.

Stage Two: Risk Assessment

The risk assessment step comprises a top-down analysis of narrative scenarios and possible futures; a bottom-up analysis of exposure, sensitivity, and adaptive capacity; and the final risk assessment, which brings these two analyses together.

Top-Down Narrative Scenarios: Exploring "Water Futures"

The first stage in the development of the risk assessment is the development of a series of potential narrative scenarios for future change. These scenarios should not be tightly bounded; that is, they are not scenarios in the sense of the economic development and emissions trajectories used by the IPCC, such as the "A1B scenario." Instead, narrative scenarios here refer to qualitative or semiquantitative "stories" of directions for future development, with explorations of the interactions of those futures with climate change.

The assessment will need to include future hydrological scenarios and the impacts of these changes on environmental flows. Thus, a hydrological component for the larger analysis is critical. Where an ecosystem vulnerability assessment is being undertaken as part of a broader project vulnerability assessment, hydrological models are already likely to have been developed. Where this is not the case, a useful risk assessment can still be undertaken without the need to develop complex and expensive hydrological models.

Hydrological scenarios or narratives should not focus only on changes to annual average precipitation or runoff. Many of the most important changes to freshwater ecosystems are likely to occur as a result of sub-annual or even sub-monthly changes in runoff or as a result of shifts in variability, such as a change in the frequency of extreme precipitation events.

An assessment of the impacts of climate change on water resources needs to consider three different dimensions of the interaction between water availability and water demand:

1. The current (baseline) situation, with respect to the availability and requirements for water, considering existing and historical hydrological variability, water demand patterns, and water resources infrastructure development

2. The likely impacts of future social and economic development on water availability (changing hydrology, etc., and proposed infrastructure) and demands (changing water use patterns, etc.)

3. The likely implications of possible future climate change on water availability (primarily through hydrological change) and demands (as reflected by changing demand patterns)

The list of eight eco-hydrological impacts set out in table 2.1 can be used as a checklist to assist in the identification of key aspects of water futures.

From the climate and development futures assessments, a 2 x 2 matrix can be developed, into which the water futures are written. Where possible, key aspects of water futures should be assigned to particular basins or sub-units. An example of this type of approach is included as table 3.1 for the Okavango case study.

Bottom-Up Assessment of System Resilience

The risk assessment process also requires the identification of ecosystem sensitivities. "Sensitivity" is defined as the extent to which a small or moderate change would be likely to have a significant impact on the ecosystem. Assessment can be made against the criteria for assessment defined in stage 1 of the assessment process.

The eight key eco-hydrological impacts can again be used to provide a structure for the assessment, with sensitivity to each impact assessed and recorded for each of the basin sub-units identified in stage 1. A narrative description of some of the key sensitivities can be developed on the basis of this assessment. Where possible, this should define the parameters of the sensitivity as precisely as possible.

A valuable mechanism for helping identify key vulnerabilities in the system is to look at where the system (or a closely comparable system) already suffers from impacts or shocks from, for example, episodic drought, flood, or pollution events.

Undertaking the Risk Assessment

The final component of the risk assessment combines the top-down and bottom-up assessments to produce a risk assessment of key vulnerabilities. Outputs from the risk assessment include a ranked list of key risks to the system. One useful approach to the assessment and illustration of key risks is to construct a matrix based on the key eco-hydrological impacts from chapter 2 and the geographical sub-units identified for the risk assessment. Examples of the application of such an approach to the Okavango and the Breede are provided in tables 3.2. and 3.3.

The identified ecosystem sensitivities and, specifically, the sensitive parameters are mapped onto the water futures to identify which critical parameter values are exceeded in which water futures. This step can be more or less quantitative depending on need and the types of data available. A qualitative, risk-based approach may be deployed where resource availability or time constraints preclude the development of detailed ecological assessments.

A key aspect of risk assessment is to specify the identified risks as precisely as possible; for example, specific time windows or flow levels at which low-flow impacts will lead to impacts, or temperature parameters that may trigger eutrophic or other negative impacts. The more clearly a risk can be identified, the more it will be possible to design monitoring and response strategies to address the risk.

Stage Three: Designing an Adaptation Response

Adaptation strategies can be designed to respond to the risk assessment. The details of these strategies will depend on the assessment context and objectives and on the potential opportunities for the development of strategies.

3.2 CASE STUDY SUMMARIES

As part of the methodology used in the development of this report, a number of case studies were undertaken to test the approaches, methodologies, and conclusions that are being proposed. These included the Mekong (Siphandone–Stung Treng), Breede (South Africa), and Tocantins-Araguaia (Brazil). In addition, an in-depth assessment was undertaken of the Okavango basin in southern Africa. These case study reports have been compiled in a separate volume and are available on file. A summary of the key findings of each of the case studies is contained in this chapter. These summaries are of necessity brief and are intended to illustrate key impacts and threats; methodologies to assess intermingled vulnerabilities that balance climate change with development and other conservation pressures; and institutionally appropriate climate adaptation options for infrastructure, policy, operations, and sustainable resource and biodiversity management. In the interests of accessibility, not all the outputs and illustrations for each case study are included in the summaries below.

A number of key conclusions emerged as common across the case studies that were undertaken. These reinforced and helped to complement the issues that emerged from the literature review undertaken for the study, and contributed to the development of the recommendations in chapter 4.

The case studies show that biodiversity and climate risk and resilience are not uniform across or within basins; in all cases, certain eco-hydrological components of freshwater systems emerged as particularly (and often differentially) vulnerable or with different roles in supporting resilience. For example, in the Okavango, the Boteti pans were identified as being particularly at risk and in need of special attention, whereas the upstream delta was less so. In the Breede, the Papenkuils wetland was likely to be particularly vulnerable to temperature increases and anticipated flow changes; however, the analysis suggested that there were certain scenarios under which climate change might diminish the significant and increasing pressures on the Breede estuary. Similarly, certain areas of basins are particularly important in contributing to resilience to climate shifts: In the Okavango, for example, the Cuito sub-system is particularly important in maintaining the integrity of the system. Spatially identifying points of risk and opportunities for resilience is therefore crucial in identifying adaptation responses, emphasizing the importance of strategic assessment, and planning of water resources and water infrastructure.

While vulnerability varies across a basin, basins must be managed as whole hydrological networks, even in transboundary contexts. Risks felt in one place often arise as a result of shifts in management in another part of the system. For example, maintaining integrity in the Cuito River provides the necessary base and flood flows to maintain functioning in the Okavango delta, even if the Cubango River is more heavily developed.

Altered flows and hydrological regimes are key drivers of vulnerability; they are already shifting. The impact of air or water temperature shifts per se was identified as a less significant immediate risk, although it might prove important in shallower wetland systems.

Negative climate change impacts are typically *superimposed* on existing and emerging development drivers or come from *synergies between* development and climate change. In the Tocantins-Araguaia and Mekong rivers, for instance, dam development pressures are likely to have far greater impacts on biodiversity than the direct impacts of climate change over the next 20 years. However, rising air temperatures and more frequent droughts are likely to cause many periodically irrigated regions to shift to permanent irrigation as crop evapotranspiration rates quicken, reducing available water resources for already-stressed ecosystems. As a result, successful climate adaptation cannot focus on climate change impacts in isolation but must expand to include a wide range of economic, policy, and social contexts.

In all cases, identified adaptation options for ecosystems required interventions that addressed resource management action, core policy, and institutional issues around water resources management. Adaptation requires that ecosystems stand at the center of water resources development.

Vulnerability to water stress proved to be a key component of vulnerability to climate change. As discussed in chapter 2, increased water stress is far from being the only impact of climate shifts on freshwater ecosystems. However, those systems or components of systems that currently experience or are at risk from water stress proved to be those assessed as most vulnerable to climate shifts in the case studies. Hence, the Breede system is likely to be more vulnerable than are the Tocantins-Araguaia and Siphandone–Stung Treng case studies, where water stress is significantly less of a threat. Within the Okavango system, the Boteti pans are likely to be most at risk from climate shifts when compared to the more water-abundant remaining parts of the system.

In addition to emerging lessons for climate risk and adaptation, a number of lessons emerged from the development of the case study pilots for the application of risk and vulnerability assessment methodologies.

The case studies demonstrated that it is possible to produce useful results on reasonably tight resources and within a short time frame. Achieving this successfully depended upon creating a team with the appropriate range of skills and drawing on the results of existing analyses. Indeed, the investment of further resources in the case studies would probably not have created significantly greater certainty about future outcomes given the inherent uncertainties associated with the estimation of future climate impacts on freshwater. Some aspects of the studies would, nevertheless, have benefited from further investment of resources: The identification of thresholds and vulnerabilities could be made significantly more precise with more investigation and analysis; more important, development of detailed adaptation options requires an extensive process of analysis and consultation that was well beyond the scope of these preliminary case studies.

The importance of the bottom-up sensitivity assessment became increasingly apparent as the case studies were developed. The importance of this sensitivity assessment emerged in two respects. First, more precise vulnerabilities result in more targeted adaptation responses. Second, the uncertainty associated with future climate impacts meant that downscaled projections could provide little guidance alone as to the risks to freshwater ecosystems from climate change. In the Okavango case study, for example, different modeling approaches produced different results as to whether the basin would become wetter or drier.

The multidisciplinary expert workshop proved to be extremely useful as a synthesizing device. Identifying risks and adaptation options is technically demanding and typically involves the assimilation of significant amounts of complex data. All these case studies used one-day workshops, which may be challenging for many basins. From the experience developed in these case studies, more than one day should be set aside for this exercise.

3.3 THE OKAVANGO BASIN IN SOUTHERN AFRICA

Description of the Basin

The Okavango basin straddles four countries within the SADC region: Angola, Botswana, Namibia, and Zimbabwe (Figure 3.2). Climatically, the northwestern part of the basin, largely within Angola, is wetter, with the more southern parts of the basin within Botswana and Namibia having semiarid to arid conditions. Environmental requirements are largely focused on the Okavango delta as a Ramsar site. The physical, ecological, and institutional characteristics of the basin lend themselves to sorting the basin into five sub-catchments (Figure 3.3):

- **Sub-catchment 1**: The Cubango catchment. The underlying geology is volcanic and Kalahari sands and provides quick-response "flashy" hydrology. This area is less ecologically important but has strong economic potential centered on agricultural development and livelihoods (subsistence agriculture, fisheries, resource harvesting).
- **Sub-catchment 2**: The Cuito catchment is strongly groundwater-driven and ecologically more important. The floodplains are important for rich biodiversity.
- **Sub-catchment 3**: The Kavango River after the confluence of the Cubango and Cuito. This region has strong groundwater influences and critical floodplains. The delta is significant for fisheries.
- **Sub-catchment 4:** The delta system is a Ramsar site with rich biodiversity and social dependencies. Floods and sediment load are important to maintain ecological function in elements such as the permanent wetlands, seasonally flooded plains, and grasslands. Upstream agricultural nutrient pollution constitutes a serious concern.
- **Sub-catchment 5:** The Boteti River and pans downstream of the delta are largely driven

Figure 3.2: Basin map of the Okavango

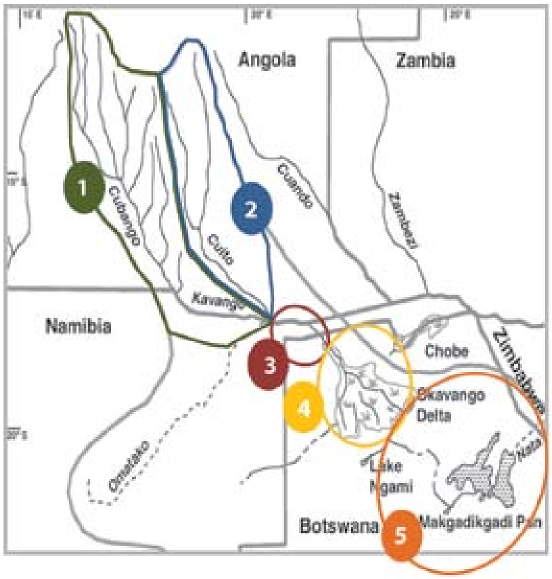


Figure 3.3: Subdivision of the Okavango into five sub-catchments (adapted from Pinheiro, Gabaake, and Heyns, 2003).

Table 3.1: Water futures for the Okavango, based on the development of future water and climate scenarios

		Development Scenarios	
		Low Growth	**High Growth**
Climate Scenarios	**Wetting**	• Higher flood flows in the Cubango and Cuito • Catchment yields in Cubango and Cuito un-impacted • Reduced dry-season flows through increased PET (balanced off on the Cuito through increased GW recharge) • Little abstraction, centered on dry-season abstraction; limited nutrient input • Adequate flow year-round to support Cubango, Cuito, Kavango, and Okavango delta • Flow into the Boteti from the delta maintained (perhaps increased) and operates almost as a permanent river	• Higher flood flows in the Cuito and Cubango • Reduced dry-season flows through increased PET (balanced off on the Cuito through increased GW recharge) • Increased abstraction, particularly dry-season abstraction, in the Cubango and Kavango • Increased nutrient input, especially during flood events (less intense) • Cuito, Kavango, and Okavango delta maintained • Flow into the Boteti from the delta maintained and almost permanently flowing, with periods where the flow is disturbed
	Drying	• Reduced floods in the Cubango and Cuito, most significantly in Cubango • Catchment yield within Cubango significantly reduced, while yield of Cuito only slightly reduced • Reduced dry-season flow in all systems • Increased abstraction, focused on dry-season abstraction; limited nutrient input • Pressure on Kavango floodplains — minimum critical flow for flooding probably achieved but extent of flooding undeterrmined • Pressure on Okavango delta — extent of flooding reduced, extent of seasonal floodplain reduced, permanent swamp under low-flow pressure • Boteti under severe pressure, reduced flow from delta, and reduced local rainfall and recharge; large stretches of the system are dry	• Significantly reduced floods in the Cuito and Cubango • Reduction in yield of Cuito minimal but of even greater significance in the Cubango due to resource development • Reduced dry-season flow in all systems; less significant in Cuito and Kavango due to groundwater recharge • Increased abstraction, particularly dry-season abstraction, in the Cubango and Kavango, and with adaptation response in the Cuito • Very little dry-season flow emerging from the Cubango • Increased nutrient input, particularly during intense flood events • Significant pressure on Kavango floodplains — minimum critical flow for flooding not always achieved, extent of flooding significantly reduced • Significant pressure on Okavango delta — extent of flooding reduced, extent of seasonal floodplain reduced, permanent swamp under low-flow pressure • Boteti River under severe pressure and dries up with no flow from delta and reduced local rainfall and recharge

by rainfall and local groundwater, with some additional release from the delta. This part of the basin has a high population density, with heavy reliance on fishing, livestock, hunting, domestic water supply, and recreation.

Water Futures

Climate scenarios for the Okavango River basin were developed, considering both global circulation models (GCMs) and statistical downscaling (SD). In general, while the GCMs predict a general decrease in rainfall, SD models predict an increase in rainfall. This divergence illustrates the difficulties of relying on the uncertainties of top-down assessments and projections. On the basis of the models developed, three climate scenarios for the Okavango River basin were derived:

- "Dry"— corresponding to the driest conditions predicted by the GCMs (i.e., the bottom of the envelope of change in rainfall and top of the envelope of change in temperature)
- "Moderate"— corresponding to the driest conditions predicted by statistical downscaling (i.e., the bottom of the envelope of change in rainfall and top of the envelope of increase in temperature)
- "Wet"— corresponding to the wettest conditions predicted by statistical downscaling (i.e., top of the envelope of change in rainfall and minimum of the envelope of change in temperature)

Sensitivity and Risk Assessment

On the basis of analysis undertaken for this case study, the systems within the basin most at risk to the different impacts of climate change are described in table 3.2.

The following broad conclusions arise from the assessment of risk and impact across the various futures:

- Owing to its heavy dependence on local rainfall and recharge, and to its downstream location, the Boteti and ephemeral pans are significantly at risk of climate change.
- Several water futures impact the delta with loss of some species and some abundance, and significant changes in the extent of the seasonal and permanent swamps. However, in none but the most extreme futures will the delta be entirely lost, with only shifting "areas" of permanent and seasonal inundation in most futures.

Table 3.2: Key risks in the Okavango system

High risk	Medium risk	Low risk
🟥	🟨	⬜

		1. Cubango	2. Cuito	3. Kavango	4. Delta	5. Boteti
Eco-hydrological Impacts	Low-flow impacts on ecosystems	⬜	⬜	⬜	🟥	🟥
	Shifts in timing of floods and water pulses	⬜	🟥	🟥	🟨	⬜
	Evaporative losses from shallower water bodies	⬜	🟨	🟨	🟨	🟥
	Higher and/or more frequent storm flows	⬜	⬜	⬜	⬜	⬜
	Shifts in thermal stratification in lakes	⬜	⬜	⬜	⬜	⬜
	Saltwater encroachment in coastal and deltaic systems					
	Increased runoff, increasing pollutants	⬜	⬜	⬜	🟥	⬜
	Hot or cold-water conditions, DO levels	⬜	⬜	⬜	⬜	⬜

- Lack of development in the Cuito buffers the impacts of climate-development scenarios on the Kavango and the delta.

- Developments in the Cubango largely impact Angola, while developments within the Cuito will have serious impacts on the Kavango, delta, and downstream pans.

Adaptation Responses

- The Cuito River is in almost-pristine condition and should have status in terms of protection, particularly given its importance in maintaining downstream integrity.

- Of the major basin states, only Namibian water legislation requires environmental allocations to be implemented as part of a water allocation process. One area where adaptive capacity could be strengthened is in strong policy and legislative support for environmental flows and the harmonization of policy among the states.

- Integration of planning among the sub-basins in the Okavango is critical. An Angolan basin strategy for the Cubango and Cuito rivers is currently under way and could serve as a useful basis to demonstrate integration of a basin-wide perspective into this national planning. Strategic environmental assessments would be a point of engagement for an investment strategy in the basin.

- OKACOM is the obvious champion of a basin-wide approach to protecting environmental flows in the face of climate change. Strong support to monitoring systems and the utilization and dissemination of information on changing flows and environmental conditions is required.

- A number of significant water resources development projects are planned for the Okavango River basin. Support to these developments should take cognizance of the strategic perspective of investment location, considering the environmental and downstream costs implicit in the development. In the context of the importance of the Cuito to the maintenance of the hydrology of the wetland, large impoundments and diversions on the Cuito River should be delayed as long as possible, when compared with development options in the Cubango River basin.

- Investment is required to increase targeted monitoring within the basin. This should include climatic, hydrological, hydro-chemical, and water use variables. For example, nutrients pose a significant threat to the Okavango delta permanent swamps. Accordingly, some monitoring of phosphorus is required at the Kavango panhandle.

3.4 THE BREEDE BASIN OF SOUTH AFRICA

Description of the Basin

The Breede River is situated in the southwest corner of South Africa (Western Cape province), has a catchment area of 12,384 km^2, and is approximately 337 km long. The topography of the Breede River basin is characterized by mountain ranges in the north and west, the wide Breede River Valley, and the rolling hills of the Overberg. The river's source catchment is in the Skurweberg mountain range above Ceres.

The basin is characterized by two rainfall patterns: In most of the basin the predominant rain falls in the months of May and August, while a year-round rainfall pattern prevails in the far southeast. The orographic influence of the high mountain ranges introduces a large spatial variability in the mean annual precipitation (MAP). In the high mountainous regions in the southwest, the maximum MAP exceeds 3,000 mm, but rainfall is as low 250 mm in the central and northeastern Breede River basin. The average potential mean annual evaporation ranges from 1,200 mm in the south to 1,700 mm in the north of the basin.

The Breede River and its various tributaries contain sensitive aquatic ecosystems and support ecologically important wetlands. The Papenkuils wetland in the upper Breede in particular is significant, as this system contains a variety of wetland and terrestrial flora that are not found or conserved elsewhere. The wetland is particularly vulnerable due to reduced water availability and retention as a consequence of local disturbances and activities within the catchments upstream. The Breede River estuary is one of the most valuable in the country but also one of the most threatened, owing to upstream development. The estuary is the nursery and recruitment zone for an extensive marine fishery and contains highly sensitive marshes and mudflats.

Land use is primarily agriculture, with large, intensive irrigation enterprises in the Breede and Riviersonderend river valleys. The Breede River basin is part of the larger Western Cape Water Supply Scheme (WCWSS), which

Figure 3.4: Basin map of the Breede

moves water around the Western Cape to provide for the city of Cape Town (CCT) and its surroundings, among others. Over 67 percent of allocable water in the basin is for irrigated agriculture, with 11 percent predominantly for urban use.

Water Futures

Water futures for the Breede were developed using a combination of development and climate scenarios:

- High-growth scenario: Increased demand requires a mixture of demand-side and supply-side interventions but with high levels of resource management to ensure sustainability.
- Moderate-growth scenario: Increasing demand, particularly in the CCT, coupled with moderate to weak water management institutions implies need for least-cost supply-side interventions
- Low-growth scenario: Increasing demand, particularly in the CCT, coupled with weak institutions and low ability to pay will drive least-cost supply-side interventions; deteriorating water quality exacerbates flow impacts

Despite disparate development futures for the Breede River basin and the Western Cape region, the impacts on the water resources of the Breede River are remarkably similar: Increasing demand, primarily for increased urban demand, requires supply-side interventions. Water quality concerns may exacerbate flow concerns (low growth), and institutional responses may alleviate some of the high-demand concerns through alternative sources and water conservation and demand management.

Given anticipated climate change effects in the Breede River basin, the following overlays can be described on the existing drivers and scenarios.

Increasing temperature will drive:

- Further increases in water demand from urban and agricultural sectors
- Increased evaporation losses from impoundments, reducing system yield
- Increased evapotranspiration in headwater catchments, reducing runoff
- Increased stress on aquatic ecosystems, particularly those poorly adapted to temperature fluctuations

Paradoxically, the mountain catchments and foothill river, which will likely see the greatest temperature changes, will be least affected, as these systems are already "naturally" exposed to (adapted to) strongly fluctuating water temperature.

Rainfall drivers:

- Possible reduced rainfall in upper catchment will reduce runoff, particularly in the dry summer season. This will exacerbate temperature and water quality effects.

- Increased variability and intensity as well as reduced frequency (bigger storms, less often) will result in dry periods punctuated by heavy falls, with resultant heavy storm flow runoff and potential destruction of habitat, particularly where already weakened by riparian or riverbed changes.

- The potential for increased rainfall, particularly summer rainfall, in the lower catchment may increase runoff in the lower catchment, particularly during the current low-flow stress period in summer. This has significant implications for the estuary, which currently suffers from very low summer flows and associated temperature and water quality impacts.

Sensitivity and Risk Assessment

The following principal risks were identified arising out of the water futures, and the vulnerabilities identified for the Breede systems.

- Demand within the Breede River basin will outstrip supply, driven by the increasing urban demand from within the Western Cape Water Supply System (WCWSS). This infrastructure response is consistent across all development scenarios. Climate change predictions (reduced runoff and increased temperature) exacerbate the supply-demand shortages in the WCWSS, reducing time before the next augmentation scheme is required. Regional transfer schemes to respond to short-term supply-demand issues, in combination with climate change impacts, will place significant pressure on the already-stressed vulnerable ecosystems (remaining mountain catchments and the Molenaars foothill river).

- Water resource development in the upland catchment of the Papenkuils wetland will further reduce flooding of the wetland, driven by increased demands within the Breede River basin and the WCWSS. Combined with land development on the verges of the wetland and maintenance of levees and berms to short-circuit water through the wetland, reduced flooding of the wetland is anticipated, with further terrestrialization and encroachment of alien vegetation. Climate change effects will likely exacerbate these effects, as they will drive increased demand for supply-side interventions. Temperature changes and water quality changes will

Table 3.3: Key risks in the Breede River Basin

High risk	Medium risk	Low risk
🟥	🟨	⬜

		1. Mountain Streams	2. Papenkuils Wetland	3. Foothill Rivers	4. Estuary
Eco-hydrological Impacts	Low-flow impacts on ecosystems	🟥	🟥	🟥	🟥
	Shifts in timing of floods and water pulses	⬜	⬜	🟥	🟨
	Evaporative losses from shallower water bodies	⬜	🟨	⬜	⬜
	Higher and/or more frequent storm flows	🟨	⬜	🟥	⬜
	Shifts in thermal stratification in lakes	⬜	⬜	⬜	⬜
	Saltwater encroachment in coastal and deltaic systems				⬜
	Increased runoff, increasing pollutants	⬜	🟥	⬜	🟥
	Hot or cold water-conditions, DO levels	🟨	🟥	🟨	⬜

likely impact negatively the already-stressed wetland vegetation, accelerating the ecological shifts in the habitat. One caveat to this scenario is introduced by the potential for increased intensity of winter floods, which may cross (or break) berms and levees, leading to increased possibility for occasional flooding of the wetland. Removal of the levees/berms, restoration activities, and management responses introduce the only real opportunities to reverse the degradation trend in the Papenkuils wetland.

- Increased demand within the basin and the WCWSS will further reduce low summer flows within the upper catchment, and will reduce winter floods required to clear the estuary mouth. Land-use changes upstream, coupled with return flow from agriculture and urban sectors, will increase water quality concerns in the estuary. These stresses are exacerbated by local impacts such as residential development around the estuary and recreational and commercial exploitation (e.g., fishing). Climate change impacts may relieve some of these stresses, as increased summer low flows may occur through increased local rainfall and runoff. Increased intensity of flood events will assist with maintaining the openness of the estuary mouth. Water quality effects will be reduced through flushing achieved in winter and through increased local summer flows.

Adaptation Responses

A number of national policy responses can be identified that will reduce the vulnerability of ecosystems in the Breede River basin and beyond. These include:

- Establishment of a precautionary determination of environmental flow standards to ensure that abstraction licenses are not over-allocated in a drier future
- Ongoing efforts to invest in demand-side solutions to supply shortages, before infrastructure investments are undertaken
- The compulsory licensing process that enables adjustment of abstraction licenses under changing conditions
- The compulsory revision of the National Water Resources Strategy (and associated local/catchment strategies) on a five-year basis, to reflect the changing conditions and imperatives in the country
- Extensive national and local monitoring programs and networks that build a baseline of information and monitor responses to changing circumstances
- Innovative non-regulatory mechanisms (economic instruments and awareness creation) that support water use efficiency (conservation) and pollution prevention

The Catchment Management Strategy (CMS) is arguably the most important instrument for adaptation planning and environmental protection, as it is the only integrated strategy at a basin level that considers all the drivers of change within the environment, taking a water perspective. The CMS is reviewed every five years, but the strategy takes a 20-year perspective, integrating water management across all water-related sectors and reflecting the broader development objectives of government and of the basin.

In addition to the national and basin-level interventions, a number of project-specific principles can be described that increase the adaptive capacity of a basin management system.

- Select more degraded locations (tributaries) for infrastructure construction to support protection elsewhere. In the Breede River basin, the Riviersonderend is an important example of this principle — it is appropriate to allow further degradation of the Riviersonderend in exchange for protection of the upland stream (mountain catchments and foothill rivers in the upper Breede). This approach will achieve both objectives of reconciling supply and demand and of resource protection within the broader basin.
- Construct infrastructure to enable adaptation by building flexibility into construction design and operation. The Molenaars diversion is an example of this principle, where the diversion design allows bypassing of the diversion scheme during low flows (summer), during wet years (winter), or under changing basin conditions (zero diversion). The relatively low cost of this diversion scheme (utilizing existing infrastructure and the passive nature of the design) implies that future decisions to bypass the scheme do not imply a significant waste of capital investment.
- Build environmental capacity into infrastructure through, for example, environmental water banking (additional releases), fish passes, and environmentally sensitive operating rules (limited/seasonal diversion).

Figure 3.5 Basin map of the Tocantins-Araguaia

The proposed raising of Theewaterskloof Dam is a local example of this principle in action in the Breede River basin, where raising of the dam wall will require significant additional capacity built into the dam to enable environmental releases from the system during the low-flow summer periods.

3.5 THE TOCANTINS-ARAGUAIA RIVER BASIN IN THE GREATER AMAZON

Description of the Basin

The Tocantins-Araguaia River basin (TARB) is situated in the north-central portion of Brazil in the greater Amazon region and spans some 918,800 km^2, representing 11 percent of Brazil. The Tocantins River is approximately 2,400 km long; the Araguaia is the main tributary, at 2,000 km. The TARB is shared by six Brazilian states (Pará, Tocantins, Mato Grosso, Maranhão, Goiás, and Distrito Federal), with 409 municipalities and almost 8 million inhabitants. Institutionally, the region manages water through both state and federal bodies, often using new or not fully defined legal instruments that do not reflect climate change, numerous stakeholders, or multi-sectoral demands. While many of these new instruments will provide some protection to natural resources, their regional application has been slow and incomplete throughout much of the TARB.

Development pressures in the TARB are complex and powerful. Barge transport is increasingly important to the region's growth. Hydropower development has been concentrated along the Tocantins, with the Araguaia left relatively intact. However, the hydropower potential in the TARB is enormous, especially if the Araguaia loses its protected status. Moreover, biofuel (sugarcane) is a large and growing industry in the region, with irrigation supplementing water supplies in many parts of the basin, as is cattle ranching. The growth of both industries in the northern, lower reaches of the TARB includes conversion of Amazon forest to fields or grazing lands, which has a strong effect on both local climate and water demand. Rapid, significant barge transport of agricultural and mining commodities is critical to development throughout the TARB, though again infrastructure construction will create conflicts with hydropower efficiency and irrigation demands, at least in some regions. Mining and other heavy industries, large irrigation projects, and extensive urban development also have significant regional impacts on water consumption, flow regime, flood potential, and sedimentation patterns.

Predicting future development is difficult for the TARB, given uncertain trends in international commodities and national energy trends. Extensive hydropower development currently looks inevitable in the region, yet realizing additional capacity presents potentially strong conflicts with irrigated sugarcane and rice in some regions of the TARB. Sediment flows are critical to the lower portions of the TARB, but these could also be disrupted by competitive hydropower water usage. Moreover, cattle ranching is less profitable than sugarcane growing, so if ethanol demand increases globally, much pasture could be converted into irrigated fields, which likely would place additional pressure on marginal lands with higher erosion potential.

Water Futures

Given the anticipated climate change effects in the TARB, the following synergies can be described:

- Further increases in water demand from urban and agricultural sectors and increased evaporative losses from reservoirs will reduce system yield. According to Mendes (2009), the decrease of mean flows downstream of Tocantins-Araguaia reservoirs will lower profitability. He simulated the following decreases of the flows downstream: –10 percent, –20 percent, and –30 percent, with respective profitability impacts of –5.42 percent, –11.64 percent, and –19.43 percent.

- Increased evapotranspiration in headwater catchments will reduce runoff. Near-surface air temperatures will increase more rapidly in the region due to deforestation, and when combined with shifts in evapotranspiration and precipitation, drying of the Amazonian portion of the TARB will accelerate (Sampaio et al., 2007).

- Decreases in mean annual rainfall will limit sugarcane expansion and shift growers from supplementing natural rainfall to using permanent irrigation during the dry season in almost all of Tocantins state. The potential competition for water use with other crops, the high costs of irrigation facilities, and decreased annual rainfall may indicate that the sugarcane activity may become economically and environmentally unviable (Collicchio, 2008).

- In both strong- and moderate-growth scenarios for the TARB, hydro capacity will increase dramatically. In the moderate-growth scenario, the capacity will reach 83 percent of the total. No published study was found related to the vulnerability of the dams and reservoirs to climate change in the TARB. However, Schaeffer et al. (2008) studied the impacts of the IPCC scenarios on the energy security in Brazil. According to Schaeffer et al. (2008), the TARB will have a roughly 15 percent decrease in annual mean runoff by the last third of this century. Such a large decline will impact capacity. The navigation sector will also be affected by reduced flow volume.

Sensitivity and Risk Assessment

Based on the climate change projections, no specific analysis was made to quantify how the expected temperature increase and precipitation decrease will affect the overall water supply and demand in the whole TARB. Even assuming a stationary climate, the high economic development foreseen for the region suggests that water demand will increase significantly and rapidly. However, by 2025 the supply will still be higher than the demand. In this sense, neither the current studies nor expert opinions considered that water transfers or diversions schemes will be developed as a future adaptation strategy.

Different conclusions appear at smaller scales. According to local experts, specific regions such as the Formosa and Javaés tributaries will present clear water conflicts due to the expansion of irrigation schemes. Also, northeastern Tocantins state and the center of Goiás state will be affected by agricultural water shortages as year-round irrigation becomes more common, triggering water conflicts.

The Bananal Island floodplain complex is particularly vulnerable to land-use changes in the upper Araguaia region. Extensive land degradation from cattle ranching magnifies soil erosion and sediment loads. This process will impact key freshwater habitat and ecological processes. Additionally, agricultural runoff (fertilizers, herbicides, pesticides) will impact freshwater species, particularly during low-flow periods. The Araguaia River is a free-flowing river. If the strong-growth scenario predominates, it will probably be maintained as a free-flowing river. Hence, the natural flow regime may not be significantly altered, though the sedimentation regime will be altered in both scenarios.

The drivers of risk are:

- Altered river flow and sedimentation regimes due to the cascade of reservoirs along the Tocantins River

- Over-abstraction of water for irrigation in the upper catchments (Araguaia and Tocantins/Paranã)

- Extreme events such as floods and dry seasons, considering the sheer scale of the TARB and the climatic variation among different sub-catchments

- Water quality degradation from nonpoint sources of pollution (urban runoff, river siltation, and agricultural chemicals)

- Intensive soil erosion and degradation in the upper catchments due to unplanned agriculture, livestock, and mining

- Deforestation of the cerrado and Amazon for agriculture and ranching

- Decrease of fisheries' stocks and spreading impacts on freshwater biodiversity due to the large-scale alteration of ecological processes such as flow regime

- Poor governance and institutional arrangements: weak structures at the state level, insufficient articulation between federal and state governments, and financial constraints due to inconsistent investments

- Social impacts due to large infrastructure development (e.g., large reservoirs displacing indigenous communities)

Adaptation Responses

- Consider maintenance of the Araguaia and Sonos as free-flowing rivers. Such rivers work as natural corridors for fish and other species and ensure auto-adaptation of ecosystems and species.

- Instituting environmental flow plans aimed at maintaining the natural flow regime (and a more natural sediment load) of the Tocantins, Araguaia, and major tributaries. This ensures habitat protection and spawning areas for fish and other species, fishing sites, and river connectivity. Environmental flow studies are necessary for that region, and capacity for implementing these actions must be expanded.

- Protect headwater and groundwater recharge areas. These areas have high potential for permanent damage as a result of strong development pressures.

- Incorporate measures to adapt to extreme events and flexible use patterns in the design of new infrastructure. For instance, although droughts are relatively uncommon in the region, developing robust drought management plans to prioritize users and ecosystem needs during these events will improve resilience. These plans may need to include insurance and alternative energy plans to maintain ecosystems as the ultimate stakeholders during severe droughts.

- Develop water supply sources in the lower Tocantins that are unlikely to face saline intrusion from sea-level rise or during severe droughts.

3.6 THE SIPHANDONE–STUNG TRENG REGION OF THE MEKONG BASIN

Physical Description of the Basin

The Siphandone–Stung Treng area is located on the main stem of the Mekong River, 50 km upstream and downstream of the international border between Lao People's Democratic Republic (Lao PDR) and Cambodia. Well-known for its biological importance and fish productivity, the region encompasses roughly 21,000 km^2 of the Mekong River and supports mostly rural populations on both sides of the border.

Within Lao PDR, the Siphandone is home to just over 100,000 people, who live in dense rural settlements spread along the riverbanks and on the islands (Daconto, 2001). Poverty levels within both the Siphandone and Stung Treng areas are high. In Mounlapamok district, where the Siphandone area lies, between 40 and 50 percent of households fall below the village-level poverty line (Epprecht et al., 2008). While market exposure and access are growing, there is very little commercial or industrial production in the Siphandone–Stung Treng area. As a result, individuals and communities within the area depend heavily on subsistence cultivation and fishing (Try and Chambers, 2006).

The following ecosystems and habitats were identified as critical and defining ecological aspects of the Siphandone–Stung Treng case study area:

Sand formations — Sandbars, sand beaches, and sandy islands in the Siphandone–Stung Treng area shift according to seasons and flood patterns in the basin and provide important habitat for a variety of species (Bezuijen et al., 2008). In the dry season, the banks are also used by local communities for vegetable cultivation (IUCN, 2008b).

Water channels — Permanently flooded areas in the Siphandone–Stung Treng area such as the Hou Sahong channel are critical for maintaining aquatic habitats and serving as a corridor for fish migration in the dry season (Warren et al., 1998). Water channels also provide water for local communities as well as avenues for transportation and sites for recreation.

Deep pools — Pockets of deep water within the Mekong riverbed provide important habitat and refugia for many migratory species in the basin, including dolphins and a variety of migratory fish, including the Mekong giant catfish. Estimates suggest that roughly 75 percent of fish caught downstream in Tonle Sap depend on migration to deep pools in the case study area for dry-season refuge (Poulson et al., 2002).

Flooded forest — Seasonally flooded forests in the Siphandone–Stung Treng area comprise various forest types whose vegetation ranges from small, aquatic herbs to trees over 15 m tall. These forests serve as important habitat and refugia, supporting a wide range of animal species (Baird, 2007; Mollot, 2005).

Gallery forest — Forests found above the high-water mark in the case study area comprise a mixture of mixed evergreen, seasonally deciduous, hardwood, and bamboo and provide critical habitat for many species.

Rapids, rock outcrops, and waterfalls — The flow of water along steep and narrow channels in the Siphandone–Stung Treng area creates accelerated and turbulent flows. The rapids and waterfalls this creates are critical to the upstream and downstream migration of fish in the basin, particularly during the dry season (Roberts, 1993; Baird et al., 2004). These areas are also important for fish catch and tourism (IUCN, 2008c).

Water Futures

The Greater Mekong subregion is expected to become slightly warmer over the next century, with warm periods extending in duration and covering much wider areas (TKK et al., 2009). While accurate information of the climate change situation at the national or sub-national level is limited in the basin, both Lao PDR and Cambodia are expected to experience a significant increase in mean annual temperature over the next century (MRC, 2009; TKK et al., 2009).

Rainfall patterns in the basin are expected to fluctuate in the first half of this century and increase over the latter half due to increases in the intensity of rainfall during the wet season (May–October) (TKK et al., 2009; Hoanh et al., 2004). Uncertainty remains regarding the effects of climate change on dry-season precipitation patterns. Recent analysis by TKK et al. (2009) suggests that dry-season precipitation will increase in northern catchments within the basin and decrease in southern catchments, while Nijssen (2001) and

Figure 3.5. Basin map of the Mekong. The Siphandone–Stung Treng region is identified within the red oval.

Hoanh et al. (2004) suggest that, throughout the basin, the driest months will become drier. Chinvanno (2008: 110) also notes the likelihood of a potential seasonal shift, with the wet season beginning in June instead of May and lasting through November.

Anticipated precipitation changes are likely to contribute to variation in runoff and discharge within the Mekong basin and alter the current flow regime and flood pulse system in the LMB (TKK et al., 2009; Hoanh et al., 2004). Overall, the increase in precipitation and runoff is expected to maintain or improve annual water availability in various catchments, though pockets of dry-season water stress (particularly in northern Thailand and the Tonle Sap region of Cambodia) are expected to remain (TKK et al., 2009; Kiem et al., 2008). Additionally, in both Lao PDR and Cambodia, flooding and droughts are expected to increase in frequency, severity, and duration (MRC, 2009; Eastham et al., 2008).

Recognizing that climatic changes constitute just some of the multiple changes driving water quantity, quality, and timing in the basin, climatic variation in the Mekong River basin is expected to affect water resources and ecosystems in numerous ways. Shifts in the onset of the wet season (from May to June) may delay the onset of flood flows in the basin. Additionally, increasing temperatures in the basin are expected to contribute to increased evaporation from the basin and a rise in water temperature, particularly in shallow ponds and wetland areas. Finally, increased intensity of wet-season rainfall is likely to drive bank erosion and contribute to increased seasonal sediment load.

Sensitivity and Risk Assessment

Analyzing water futures in the Mekong River basin highlighted the relative impact of development and climatic changes on the Siphandone–Stung Treng area. In doing so, it revealed that the impacts from economic development throughout the basin are likely to be far more influential in altering ecosystems and livelihoods in the case study area, particularly in the short to medium term.

The high-development scenario includes four major dams that have been proposed within or near the Siphandone–Stung Treng area: the Lat Sua and Don Sahong dams in Lao PDR and the Stung Treng and Sambor dams in Cambodia. Workshop participants identified several impacts from these proposed dams on ecosystem components within the case study area. Primary projected impacts include loss of connectivity, altered timing and water quality, and inundation of ecosystems within the area. The further expansion of agriculture and settlements in the case study area is also likely to have a significant impact on the ecosystem components.

Adaptation Responses

The knowledge base regarding the nature and effects of demographic, economic, and climatic changes in the Mekong River basin is rapidly increasing. Nevertheless, there is still appreciable uncertainty surrounding our understanding of the magnitude of anticipated changes; the impact of these changes on water resources in the basin; and the secondary effects on ecosystems, agriculture, energy, and human health.

Given its position in the mainstream of a dynamic transboundary river, the Siphandone–Stung Treng area is vulnerable to changes occurring upstream and downstream in the Mekong basin. Consequently, successful adaptation at the local level will need to be reinforced by sound resource management at national, multilateral, and basin-wide levels. This could include:

- Bridging gaps in communication and coordination. Despite the interdependence of different government ministries, sectors, and user groups at various scales, existing governance arrangements within Lao PDR and Cambodia could be strengthened to facilitate dialogue, planning, implementation, and monitoring.
- Accounting for ecosystem services in decision making. The broader integration and valuation of ecosystem services into the research and decision-making process will help policy makers engage in strategic planning with the capability of taking a more comprehensive view of the costs and benefits over the short and long terms.
- Infrastructure placement design and operation. According to workshop participants, most of the existing infrastructure in the case study area, including roads, houses, and bridges, are well-equipped to deal with the seasonal fluctuations of the dynamic Mekong River. Particular considerations for the implementation of new hydroelectric dam projects in the area include the siting of the project, the timing and temperature of releases, and sediment capture.
- Investment in natural infrastructure. Protecting the mosaic of ecosystems that comprise the Siphandone–Stung Treng area is critical for decreasing vulnerability and enabling adaptation.

4. RESPONDING TO CLIMATE CHANGE

Many of the most significant measures required to support successful adaptation to climate change will be familiar from current best practices in water resources management (World Bank, 2009). Climate change provides a compelling further reason to overcome the barriers to the implementation of these approaches. At the same time, the prospect of climate change provides a number of motivations for approaching water management with a new focus.

This chapter develops recommendations for supporting climate adaptation for freshwater ecosystems in two stages. First, a framework for considering adaptation responses is set out, based on a risk-based approach to water management. Second, general management objectives are identified that are likely to support successful adaptation. These provide overall objectives for water management institutions to pursue in seeking to support adaptation. Third, more specific recommendations for potential World Bank support to the achievement of these objectives are provided.

4.1 A FRAMEWORK FOR CLIMATE ADAPTATION — A RISK-BASED APPROACH TO WATER MANAGEMENT

Chapter 2 emphasized that climate change impacts on freshwater systems will be characterized by high levels of uncertainty, over both short- and long-term time horizons. Consequently, a risk-based approach to water management and adaptation is recommended. This requires a revised approach both to water infrastructure development and water resources decision making, and a risk-based approach to the development of adaptation measures.

First, the maintenance of freshwater ecosystems has always implied the need to account for trade-offs, taking account of the important services offered by healthy ecosystems in development decision making. However, uncertainty about future climate trajectories creates new challenges in ensuring that ecosystems have the resilience and flexibility to respond to change. These challenges center on balancing "traditional" pressures (especially water supply and demand for multi-sectoral uses of water) with the recognition that most freshwater systems are already or are likely in the near future to experience climate change pressures, and that these pressures will increase in the future in ways that will not always be clear in advance. Inevitably, recognizing and integrating these elements into a decision-making process means adopting a different approach to trade-offs. In the words of the most recent World Development Report,

> Accepting uncertainty as inherent to the climate change problem and robustness as a decision criterion implies changing decision-making strategies for long-lived investment and long-term planning. It demands rethinking traditional approaches that assume a deterministic model of the world in which the future is predictable. (World Bank, 2010b)

Ensuring that freshwater ecosystems have the resilience to adapt implies the need to accommodate significant additional assimilative capacity in ecosystems. The 2010 World Development report identifies the need for "safety margins" to be built into decision making, and this consideration applies to ecosystem adaptation and socioeconomic development. For example, basin-wide infrastructure development strategies may need to leave greater accessible refugia for species to respond to a changing climate, implying the need to ensure that impacts on connectivity from new infrastructure within the basin are minimized. Alternatively, agricultural development planning may need to proceed on the assumption of reduced future availability of water resources from a basin, thereby ensuring that planned development does not compromise future environmental water needs. In each of these cases, risks from future climate change imply the need to give increased weight to the maintenance of ecosystem functions in the trade-offs inherent in development decision making.

Second, a risk-based approach to the design of adaptation measures requires not a static set of interventions but instead an understanding of the range of potential future risks and a monitoring and adaptation strategy that is able to identify and respond to risks as they materialize. An approach based on risk assessment and adaptive response can represent a significant change in approach compared to more deterministic approaches to water resource management. A risk-based approach to adaptation can be implemented only when there is an understanding of the risks to ecosystems. Negative impacts of climate change on ecosystems are likely to occur through the impacts of particular climatic and hydrological events on particular parts of ecosystems; different ecosystems will be vulnerable to differing possible changes in different ways.

The 2010 World Development Report identifies three broad strategies that can enable robust adaptation under uncertainty: shaping strategies, hedging strategies, and signposts. These three approaches can help to frame adaptation strategies for freshwater ecosystems.

Shaping Strategies: Implementation of Adaptation Measures for Identified Risks

Mitigation measures may be undertaken immediately for some risks. This may be an appropriate response under a number of circumstances:

- **Low-regret measures**. Many adaptation responses have multiple benefits, such as pollution reduction efforts or improved water resources management. These types of measures are often grouped together with win-win measures and can be undertaken immediately, even when there is considerable uncertainty.

- **Climate-justified measures**. Some future risks may be assessed as having a high likelihood. In these cases, adaptation measures can be initiated immediately. In other cases, adaptation responses will have long implementation lags. This is most characteristic of infrastructure construction, where decisions need to be made now that will be embedded for several decades. For example, the design of the capacity of urban storm drains requires an assessment of future climate risks. In addition to infrastructure construction, many longer-term policy reforms can require decades to implement. For example, changes to water allocation and water rights systems to allow for greater flexibility typically require reform processes over many years.

Hedging Strategies: Adaptive and Enabling Measures

For many risks, immediate implementation of measures may not be appropriate because there is too much uncertainty about the benefits. However, it may still be sensible to undertake preparatory measures so that the required response can be activated when the level of uncertainty is reduced or the risks of not implementing the measure become too great. In many cases, adaptation will not occur if these preparatory measures are not undertaken.

For example, one of the primary adaptation challenges in freshwater will be the need to respond to increasing variability of precipitation, with potential low-flow impacts on freshwater ecosystems. Damage to ecosystems may be

Box 4.1: Declining fisheries of the Rift Valley lakes: a climate change phenomenon

Various studies demonstrate the dramatic effects that changing temperature can have on fish biomass in lake ecosystems and the associated socioeconomic effects of a declining fishery. Lake Tanganyika is the world's third-largest freshwater lake, at 19,000 km3, and the second deepest, at almost 1,500 m. It is home to a rich biodiversity of over 500 cichlid and other fish species, many endemic. In addition, the lake has a productive pelagic fishery supporting over 100,000 fishermen and providing up to 40 percent of protein intake for the catchment's more than 1 million inhabitants. The lake has historically supported one of the world's most productive pelagic fisheries, with a recent annual harvest of between 165,000 and 200,000 metric tons and an equivalent value of several tens of millions of US dollars. As in many lakes worldwide, this once-productive fishery has collapsed in recent years, with dramatic effects on the lake ecology and on local livelihoods. This commonly was thought to have been the result of overfishing, but evidence published in Nature demonstrated a linkage between this collapse and the changing climate of the Central and East African rift valleys.

Owing to its great depth and its physical characteristics, the lake is oligotrophic and permanently thermally stratified with an anoxic hypolimnion that is described as "fossil water." Surface waters are fed with crucial nutrients, predominantly phosphorous and silicon, during the cool and windy winter and spring months, when the thermocline is weakest, and upwelling of deeper (nutrient-rich) waters occurs in the south. O'Reilly and colleagues (2003) described the effects of increased surface temperatures and reduced wind activity on this nutrient cycling. They showed that the markedly reduced enrichment of surface water was attributable to increased stratification and reduced wind activity following increased winter surface water temperatures. The reduced nutrient input to the pelagic food chain was a factor in the collapse of the fishery, together with the heavy fishing pressures. This research demonstrates that the effects of a changing climate are already being experienced in one of the African Rift Valley lakes.

Source: O'Reilly, 2003

avoided if water use can be reduced in response to annual or seasonal variations in water availability, or if stored water can be released to maintain flow levels. In these ways, environmental flows can be maintained in the face of a year of below-average precipitation. However, in order for this to happen, there needs to be sufficient flexibility within the water management system to enable such an adaptive response. Management rules need to be designed to allow water demand to be altered in response to conditions, accompanied by the establishment of monitoring programs that can detect changes in time.

Preparatory and enabling measures therefore typically consist of three steps:

- Identify potential risks to the ecosystem as clearly as possible, along with a monitoring protocol and indicators that will indicate when action may be required.
- Develop response rules that set out actions that will be taken when indicators are passed.
- Develop the ability to respond to and implement necessary adaptation measures; for example, flexibility of allocation, demand reduction options, flexibility of dam operating rules.

Signposts: Monitoring Measures

A key element of a risk-based management approach is to install a strong monitoring and analysis process that is able to identify when and how change is happening. In most cases in developing countries, even the basic hydrological monitoring networks are very weak or have fallen into disrepair. The monitoring data needs to be analyzed so that changes can be identified and fed into management decisions. In addition, a regular strategic review of risks needs to be undertaken to allow for adaptation planning to be updated.

4.2 MANAGEMENT OBJECTIVES FOR FRESHWATER ADAPTATION

Many professional bodies and institutions are providing sector-specific and cross-sectoral guidance to assist and operationalize adaptation measures. They typically distill and translate the latest scientific knowledge into workable strategies for practitioners while also being mindful of policy and legal contexts. Guidance ranges from "rules of thumb" (such as ***Incorporate more green space in urban designs to reduce heat stress***) to tables of prescribed standards for engineers (such as the UK government's ***Add a 20 percent sensitivity allowance to daily rainfall, peak river flow volumes, and urban drainage volumes to account for climate change by 2050***) (Greater London Authority, 2005; Department for Environment, Food, and Rural Affairs 2006). Other guidance depends on case studies to show practical examples of adaptation within a particular sector or to share lessons learned by different countries (Pittock, 2008; Hellmuth et al., 2007; European Environment Agency, 2007). Some guidance is delivered as sets of principles and primers; other guidance is available via online resources that share practical insights based on local coping strategies (Miller and Yates, 2006; Matthews and Le Quesne, 2009; UNFCC, 2008). Field- and community-level projects are also regarded as powerful vehicles for demonstrating adaptation in action or for highlighting the immediate and longer-term benefits of tackling non-climatic anthropogenic stressors (Hansen and Hiller, 2007). Some guidance sets out general adaptation measures that can be used to counter specific challenges, such as rising water temperatures or the changing hydrology, hydromorphology, and water quality of freshwater bodies.

In constructing the approach here, we build on the characterization of the key impacts of climate change on ecosystems presented in chapter 2 and the general principles for adaptation in freshwater that have been developed elsewhere (WWC, IUCN, and CPWC, 2009; GPPN and SIWI, 2009).

Institutional Capacity

Building strong institutions with the right institutional framework and administrative and technical capacities is a crucial precondition toward adapting to changes in climate (World Bank, 2009). This is equally true when building climate change adaptation into the management of freshwater ecosystems. One of the crucial barriers to the achievement of the management objectives outlined in this chapter is the lack of adequate data and information and core technical and administrative capacities in water resource and environmental management institutions, especially the environmental, ecosystem, and biodiversity components of water management.

Required institutional capacity can be characterized in terms of three related areas:

- *Enabling frameworks and institutions*. Successful adaptation, whether for ecosystems or broader social

Box 4.2: The ebb and flow of Australia's Murray-Darling basin: state change and environmental flow priorities

The Murray-Darling basin in southeastern Australia covers a seventh of the continent's landmass. Wetland protected areas extend across the basin, including 16 Ramsar sites. The low levels of rainfall in the current "drought" in southern Australia are unprecedented in the century-long instrumental record, and inflows into the river systems are at an historical low. A number of agencies now describe the drought as being exacerbated by, or due in part to, climate change and worse-than-historical droughts (Timbal, 2009; SEACI, 2008; Cai, 2008). In addition, it is likely that the combination of greater evapotranspiration with higher temperatures and inflow-intercepting land uses has dramatically reduced runoff. The case provides a vivid example of the types of rapid state shift that can be manifest in freshwater climate change (Cai, 2008).

The environmental flow provisions on the rivers of the basin have failed to protect ecosystems from the reduced runoff. Since 2006, two key states — Victoria and NSW — have suspended environmental flow rules. Even without this suspension, CSIRO (the government research organization) says, "Current surface water–sharing arrangements in the MDB would generally protect consumptive water users from much of the anticipated impact of climate change but offer little protection to riverine environments." (CSIRO 2008) In other words, the environment would suffer a disproportionate reduction as water allocations are reduced with climate-induced scarcity. This concern is reinforced by the National Water Commission, which expressed concern at lack of security for environmental water during drought and has called for environmental watering protocols that apply under all inflow scenarios (NWC, 2009).

As a result, the Coorong Ramsar site and many other wetlands are increasingly desiccated. The Coorong estuary is separated from Lakes Alexandrina and Albert by a barrage system to prevent upstream seawater intrusion into the lakes. The Coorong and Lakes Alexandrina and Albert have undergone significant changes in ecological character over the past decade. Lake Alexandrina is now 0.5 m below sea level behind the barrages and would require around two years of average river flows to refill.

This drying out has produced some nasty surprises. High salinity levels were expected in the lakes, but an invasion of marine bristle worms wasn't, and the worms have colonized the shells of eastern long-necked tortoises with massive encrustations, leading eventually to their deaths. Exposed wetland sediments high in sulfates are oxidizing, producing sulfuric acid. Around 3,000 hectares of the lakes' shorelines are affected, and as the damage spreads up the Murray River valley, up to a quarter of other wetlands are impacted. At Bottle Bend Lagoon near Mildura, for example, the water now has a pH of 1.6.

Source: Jamie Pittock, Australian National University

objectives, will require that a series of key enabling institutions be in place. For example, the existence of an effective, enforceable, and adaptive water allocation mechanism is an essential prerequisite for effective water resources management under changing climate conditions, including the maintenance of environmental flow conditions. A range of such enabling institutions exists, including effective short- and long-term water and infrastructure planning and permitting mechanisms and frameworks.

- *Organizational capacity*. Effective water management requires the existence of effective and functioning water management institutions to discharge a range of functions, including planning, permitting, and enforcement.
- *Monitoring and assessment*. Central to successful efforts to adapt to climate change will be the ability to identify and analyze changes as they are occurring, so that response mechanisms can be identified and triggered. This is likely to require a range of monitoring efforts, including basic meteorological and hydrological monitoring, water quality monitoring, and monitoring of ecosystems. For example, the need for improved water quality monitoring was identified as one of the key recommendations in the Okavango case study undertaken for this report.

Unfortunately, institutional capacity across all these areas is currently a significant challenge in many water resources and environmental management contexts, and this is likely to represent a significant barrier to effective adaptation in many contexts.

Maintaining Environmental Flows

The highest priority climate adaptation measures for freshwater ecosystems are the protection and maintenance of environmental flows, in particular in regulated rivers or systems subject to significant water abstraction. This requires policies and implementation measures to protect and restore flows now and to protect an environmental flow regime in the future under changing patterns of runoff. Both are significant policy and legal challenges.

It is increasingly recognized that implementation is an iterative process requiring action at a number of levels: at a policy level, recognizing environmental needs in the mechanisms controlling the management of water abstraction, the operation of existing infrastructure, and the construction of any new infrastructure; and in catchment and infrastructure management plans.

In order for ecosystems to be protected, environmental flow requirements may need to be granted a high priority in the allocation decisions and recognized as a prior allocation that needs to be enforceable. Where environmental flow requirements are not recognized as a prior allocation, reduced river flows as a result of climate change will often lead to consumptive water receiving preferential treatment and environmental water being disadvantaged, with the potential for attendant environmental damage. This applies to both water resource management and infrastructure operations. Finally, environmental water allocation needs to be enshrined in law as a water right that is enforceable, as is the case in the South African water policy.

The recognition and protection of environmental flows under conditions of increased climate variability pose a particular challenge. They require a water rights system and dam operating rules that retain sufficient flexibility to adjust water use in both the short and long terms, in response to changing runoff, with guarantees in place to protect environmental needs as availability changes. An adaptive management system that protects environmental flows under future climate variability therefore needs to be designed into the heart of water rights, allocations, and infrastructure design and operating rules. Recognition of the potential for future variability also needs to be considered in transboundary agreements.

Early support for environmental flows through policy implementation is important. The establishment of environmental flow allocations will be cheaper and politically more tractable if the authority is established before significant climate change occurs. Establishing and implementing these policies at a later stage is likely to require expensive and politically contested reallocation processes under conditions of increasing conflict and resource pressure. This adds to the urgency of introducing environmental flows as a key element of water sector reform in those countries where such processes are not yet in place.

Reducing Existing Pressures and Protecting Resilient Ecosystems

Impacts from climate change and human-induced non-climate pressures will affect both individual species and ecosystems. The species that will be in the strongest position to adapt to climate change are likely to be those that occur in healthy freshwater ecosystems, as those systems will retain the greatest assimilative capacity.

Reducing pressures that cause ecosystem decline is, therefore, a critical part of building the resilience of ecosystems in the face of climate change. Measures to protect ecosystems include reduction of water demand; increase in water efficiency measures; restoring more natural river flows so that freshwater ecosystems are not vulnerable

Box 4.3: Reducing the risks of eutrophication

Increased water temperature due to low flows, higher air temperatures, or both increases the risks of eutrophication of freshwater systems. This risk is most pronounced in systems already suffering from excessive or increased nutrient levels. Central to the development of increased resiliency in these systems is a reduction in pollution levels, so that these systems are in as strong a position as possible to withstand increasing air and water temperatures.

The region around Wuhan on the middle Yangtze was formerly rich in wetlands and lakes, but these have been surrounded by urban and industrial development over recent decades as human populations have grown and the local economy has shifted. Pork production is extremely important in the region (an average farm has more than 10,000 pigs on the shore of the river or a lake), and intensive aquaculture is also important to the region. Given the amount of poorly treated or untreated pig and human waste and fish food entering these lakes, algal blooms, which were once rare events in summer, have now begun to occur even in the cold winters of the Wuhan region. These problems will become far more severe if both air temperature and droughts become more variable.

WWF's China Program Office has been working closely with local pork and fish farmers and government officials to create pilot projects that reduce nutrient inputs, and to use water infrastructure to "flush" these wetlands and lakes with main stem river water, reducing their propensity to develop low-water concentrated solutions. This process effectively reproduces the natural interconnection between the wetlands and river that existed before the construction of hard infrastructure.

to small, climate-induced changes in runoff; and reduction in other pressures such as pollution, invasive species, and overfishing.

The assimilative capacity of freshwater ecosystems will be further increased where a diversity of healthy habitats can be maintained within a river system. This increases the likelihood that the system will be able to withstand different types of impact. In reality, this is likely to mean maintaining a combination of healthy tributaries across the basin, along with some parts of the main stem of the river. The maintenance of connectivity between different healthy sub-systems within a basin, so that they can act as refugia in response to climate shocks and permit re-colonization of the basin following shocks, is likely to play an important role in contributing to adaptation.

4.3 OPTIONS FOR INTEGRATION INTO WORLD BANK ACTIVITIES

The achievement of these management objectives in any given water resources management context ultimately depends upon the commitment, resources, policies, and laws of national, transboundary, and local political and management authorities. Successful adaptation will require that the necessary interventions be locally led, supported, and implemented. Given that the primary responsibility for adaptation lies in national and transboundary governments and authorities, there are significant opportunities for the Bank to further the achievement of these objectives where there is appropriate support for these approaches from national and transboundary authorities. Opportunities exist in both project lending and the Bank's portfolio of sectoral adjustment lending and technical support.

The World Bank report (World Bank, 2009) identifies potential areas for the Bank to provide support to climate adaptation in the water sector, including policy and institutional intervention, technology, water management, infrastructure, monitoring/information systems, and capacity building/awareness. The recommendations set out below cover many of these areas and are divided into the principal areas of World Bank activities: project lending; policy, program, and technical assistance; and research and development of knowledge. Opportunities also exist outside the water sector, particularly by supporting national and transboundary environmental programs. The potential activities could form important component elements of any future cross-sectoral adaptation support.

The potential areas for support identified here are consistent with many of the conclusions of the Bank's mid-cycle Implementation Progress Report for the Water Resources Sector Strategy (World Bank, 2010c). Key common recommendations include an emphasis on integrated and strategic planning in the context of climate variability and change, and an increased focus on water quality and monitoring.

Many of the core interventions needed for ecosystem adaptation build on the significant developments in sustainable water resource management that have emerged in recent years. Many of these methodologies have received important conceptual and practical support from the Bank, including support for environmental flows and strategic environment assessment. Nevertheless, significant opportunities remain for the further development and trialing of many of the methodologies underlying the adaptation options outlined in this paper, an endeavor to which the Bank could contribute. A number of related areas in particular would benefit from further research and development:

- Despite significant progress in recent years, there remains further work to be done in developing practical environmental flow assessment methodologies, in particular for large rivers, and reliable approaches that can be undertaken with limited resources. Development of these methodologies will assist in identifying key thresholds of concern for future water stress in major basins.

- As highlighted in both the theoretical discussion and the case studies in this report, maintenance of function in key parts of freshwater systems is likely to be crucial in supporting resilience to both climate and development pressures. Early development of methodologies has taken place to identify these areas of freshwater systems, but significant further development is required, in particular to develop methodologies that are practical to apply and can develop solutions and recommendations that can inform basin planning efforts in a meaningful way.

- The development of vulnerability and risk assessments, and the incorporation of these into strategic assessments and basin planning approaches, remain in their infancy. Significant further development work remains to be done..

Projects

There are significant opportunities for incorporation of ecosystem adaptation measures into the Bank's extensive portfolio of project-level lending, most significantly in Bank lending for water infrastructure but also in the context of some sectoral projects that impact freshwater resources such as irrigation expansion.

Environmental Flows

The provision of environmental flows should continue to be incorporated as a core issue in the World Bank's water infrastructure project lending. Thorough recommendations on opportunities for the Bank to support improved protection of environmental flows across projects, plans, and policies have been set in a recent publication, ***Environmental Flows in Water Resources Policies, Plans, and Projects*** (Hirji and Davis, 2009a). The project-level opportunities identified in that report include the following:

- Disseminate existing guidance materials concerning the use of environmental flow assessments (EFAs) in program and project settings, and conduct training for Bank and borrower country staff on application of EFAs.
- Develop an environmental assessment update (an operational guidance note) on EFAs.
- Identify settings, approaches, and methods for the select application of EFAs in the preparation and implementation of project-level feasibility studies and as part of the planning and supervisory process.
- Prepare a technical note that defines a methodology for addressing downstream social impacts of water resources infrastructure projects.
- Test the application of EFAs to include infrastructure other than dams that can affect river flows, as well as other activities such as investments in large-scale land-use change and watershed management and their associated effects on downstream flows and ecosystem services.
- Undertake appropriate pilot projects to include all affected downstream ecosystems, including groundwater systems, lakes, estuaries, and coastal regions.
- Develop support materials, such as case studies, training material, technical notes, and analyses of effectiveness, for Bank staff and counterparts in borrowing countries.

Sustainable Infrastructure Planning and Design

The design, siting, and operation of water infrastructure will be central to determining the extent to which freshwater ecosystems are or are not able to adapt to future climate shifts. The uncertainty inherent in future climate scenarios has implications for both new infrastructure as well as the rehabilitation and re-operation of existing infrastructure. Supporting adaptation in freshwater ecosystems implies that new infrastructure should not unacceptably impact the adaptive capacity and resilience of freshwater ecosystems. Negative impacts may result both from changes to environmental flow regimes and from reductions in connectivity and refugia within freshwater systems as a result of new infrastructure.

Concerns over climate change and the impacts on environmental flows reinforce the importance of including environmental flow needs in infrastructure development projects supported by the Bank. In order to maintain healthy ecosystems downstream of water resources infrastructure such as dams and weirs, environmental flow assessments should be integrated into environmental assessments undertaken for infrastructure projects supported by the Bank. Similarly, assessments and measures to minimize impacts on connectivity and downstream habitats will assist in helping to ensure that the adaptive capacity of freshwater ecosystems is not impacted significantly by infrastructure development projects. Thus, the effects of infrastructure on the transport of sediment and the maintenance of physical habitat on floodplains and in estuaries and deltas should be accounted for in these environmental assessments. All projects on international waterways will be subject to OP7.50 and BP7.50, which require that early notification be given to riparian countries of any proposed project.

Both of these considerations may imply affording a stronger weight to ecosystems in the trade-offs inherent in infrastructure decision making. In some cases, infrastructure may appear to underperform with current climate conditions because design parameters suggest that future water availability will be quite different from the present.

There are opportunities to account for the potential impacts of climate on three places in infrastructure planning:

- *Impact assessment*: Impact assessment provides the core mechanism by which a full consideration of the impacts of infrastructure on future adaptability and resilience can be considered. This can include an assessment of the impacts of climate change on environmental flows; an assessment of potential future shifts in ecosystem and species distribution; and an assessment of the potential impacts of new infrastructure on the capacity of ecosystems to adapt to these changes, including the siting of that infrastructure.

- *Design*: Design of infrastructure can be crucial in dictating whether, and the extent to which, infrastructure is capable of facilitating adaptation to future climate shifts. In practical terms, this is likely to mean that infrastructure should be designed to be built and operated with more flexibility in order to encompass a number of differential future climate states. Technological advances in dam design are central to this emerging concept of "flexible infrastructure." These approaches can apply both to new infrastructure and to the rehabilitation of existing infrastructure. Some of the characteristics of infrastructure design that can contribute to the achievement of these objectives include:

    - Dam design and outlets with sufficient capacity to permit a range of environmental flow releases

    - Multi-level offtakes to control temperature and chemical pollution and to permit releases under a range of different conditions

    - Fish passages

    - Sediment outlets or bypass facilities

  Consideration should also be given to the design of redundancy in infrastructure to accommodate future hydrological variability. The inclusion of capacity to permit storage for future environmental flow releases provides an important opportunity for new infrastructure to play a positive role in supporting adaptation.

- *Operating conditions*: In order to protect environmental flows under conditions of future variability, dam operating rules need to retain flexibility, with specific provisions for the protection of environmental flow needs as water availability changes. The Bank could support the inclusion of these flexible operating rules as a deliberate attempt to test and demonstrate options for managing infrastructure.

A growing body of literature and experience, some of it supported by the Bank, underpins many of these approaches. Krchnak, Richter, and Thomas (2009) provide more specific recommendations on the incorporation of environmental flows into hydropower infrastructure planning, design, and operations. Ledec and Quintero (2003) emphasized the importance of selecting the location of dams to minimize their environmental impacts. These more detailed recommendations have the opportunity to provide guidance on how to assist in building resilience to climate shifts into ecosystems downstream of dams.

In many cases it may be too late to protect aquatic ecosystems through environmental assessment and design when infrastructure projects are being built. The important decisions have already been made by that stage, including the siting of the infrastructure (Ledec and Quintero 2003). Moreover, the ability of freshwater ecosystems to adapt to climate change is improved where infrastructure projects are designed and operated at a basin and/or on a system-wide scale, particularly if operations assessments include multiple sectors across the basin. This can provide opportunities for whole-system operations that are able to meet environmental and economic needs under future hydrological variability. Where the infrastructure on a river system is operated together in an adaptive manner, there is significantly greater flexibility than if individual infrastructure is operated independently. Strategic basin-level planning of infrastructure is therefore likely to be important in determining the extent to which infrastructure is able to contribute to or hinder adaptation of freshwater ecosystems.

Projects and programs to re-operate infrastructure can also play an important role in supporting adaptation. This can include alterations to infrastructure design, facilities, and operating rules at the time of re-operation to ensure that they provide maximum support to the adaptive capacity of ecosystems and that they contain mechanisms to allow for flexible operations in the future in response to shifting hydrology.

Strategic Environmental Assessment and Project Planning

The use of strategic environmental assessment (SEA) in water resources planning provides important opportunities for promoting adaptation objectives. First, SEA provides the opportunity for groups of infrastructure projects to be designed and operated in an integrated and flexible manner to achieve both ecosystem and socioeconomic objectives under a variety of futures. Second, SEA provides the opportunity to identify early in program design those parts of freshwater systems that are most vulnerable to climate change or are most significant in supporting resilience of systems to future change. This can allow for dam siting to consider and potentially avoid these areas. Third, SEA provides the vehicle by which vulnerability and risk assessment methodologies can be incorporated into project design and planning. There exist opportunities for the Bank to continue to promote the use of SEA and related assessment approaches in the context of project development processes.

To support increased use of vulnerability assessment, the Climate and Water Flagship report (World Bank, 2009) recommends that risk assessment be undertaken for infrastructure projects and their various component parts. These recommendations focus on a climate change vulnerability assessment for ***new infrastructure and its services.*** This focus could be extended to include an assessment of the vulnerability of ***freshwater ecosystems and their services*** to the combined effects of climate change and the proposed project. Put another way, the assessment could be broadened to consider whether the proposed project will increase or decrease the resilience of the associated freshwater ecosystems. The methodology described in chapter 3 provides one approach that could be used for these vulnerability assessments.

Policy, Program, and Technical Assistance

World Bank program and policy lending and technical assistance provide further opportunities to advance the key management objectives identified in this report. Opportunities within the water sector include support for policy reforms at the national level, and support for institutional improvement, capacity building, and water planning at the basin level. Opportunities also exist outside the water sector, in particular where the Bank provides support for national and transboundary environmental and adaptation capacity and policy programs. The Bank's considerable portfolio of program and policy support means that it is well-placed to support national governments in meeting these objectives.

Support for Development of Institutional Capacity

The Bank is well-placed to continue its program of support to client governments in building their institutional capacity through its lending for water resource reform and institutional development. This has the potential to facilitate adaptation in each of the three areas of capacity identified above and is likely to leverage social, environmental, and economic benefits simultaneously.

The ability to undertake monitoring and assessment is a specific part of institutional capacity that will be crucial in providing water resource management institutions with the information to adapt to climate variability, both for ecosystems and for human societies. The Bank has the opportunity to support monitoring and assessment programs that develop:

- An understanding of risks to freshwater ecosystems and of preemptive indicators
- Monitoring programs to identify changing environmental conditions
- Analysis to interpret data and provide management information to water resource managers
- Rules and systems with the capacity to respond to variability and change

Support for Environmental Flows in Policy and Water Resource Planning

Hirji and Davis (2009a) recommend that the Bank support the inclusion of environmental flows in policies and plans (especially water resources plans at the basin level). Their key recommendations include the following:

- Use CASs and CWRASs to promote Bank assistance with basin or catchment planning and water policy reform so that the benefits of environmental water allocations for poverty alleviation and the achievement of the Millennium Development Goals are integrated into country assistance.

- Incorporate environmental water needs into Bank SEAs such as country environmental assessments and sectoral environmental assessments.
- Test the use of EFAs in a small sample of sectoral adjustment lending operations, including where the sectoral changes will lead to large-scale land-use conversion.
- Promote the harmonization of sectoral policies with the concept of environmental flows in developing countries, and improve the understanding within sectoral institutions about the importance of considering the impact of their policies on downstream communities.
- Develop support materials for Bank staff on the inclusion of environmental flows into basin and catchment planning and into water resources policy and legislative reforms.
- Draw lessons from developed countries that have experience with incorporating environmental flows in catchment planning.

Support for Basin Planning and Strategic Environmental Planning of Water Resources

Robust planning mechanisms that integrate long-term environmental considerations will be core elements of enabling adaptation. Support for strong basin planning mechanisms and the integration of strategic environmental planning into national and transboundary water resource policy and planning will be crucial in helping aquatic systems adapt to climate change. As with the more general development of institutional capacity, this is likely to yield multiple important benefits for ecosystems and socioeconomic objectives. SEA that includes considerations of climate change provides an important mechanism for doing this.

The World Bank has recently re-affirmed the importance of SEA as a powerful tool for adaptation to climate change in water resource policy making (Evans, 2009). This view emphasized the ability of SEA to assess climate-induced risks in water resources institutions (e.g. river basin organizations) and in river basin planning to strengthen the capacity of institutions to respond to any climate change and to utilize participatory approaches to improve decision making.

Support for Water Resource Protection Programs

Support for river, lake, and wetlands restoration and protection programs as part of lake basin management, watershed management, and wetlands conservation projects as well as dam and water system re-operations funded by the World Bank and the GEF has the opportunity to continue to provide low-regrets responses that yield multiple benefits. These projects would reduce pressures on freshwater ecosystems while developing their capacity to adapt to climate change. Water systems re-operation offers win-win benefits that can both improve the performance of existing systems and enhance environmental and social benefits, especially to downstream communities.

GLOSSARY

Adaptation: Via initiatives and measures, the reduction of the vulnerability of natural and human systems against actual or expected climate change effects. (IPCC WG1)

Bioclimatic envelope modeling: Combines information about suitable "climate space" and dispersal capability (based on species traits) to predict the ecological consequences of different emissions scenarios.

Biodiversity: A measure of the variation of life forms within a given ecosystem, biome, or the entire planet.

Biomass: The mass of living biological organisms in an ecosystem or other geologically defined region at a given time.

Biome: A large ecological community classified according to the predominant species of plants, animals, and climatic conditions.

Climate change: A change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods. (UNFCC)

Climate model: A numerical representation of the climate system, based on the physical, chemical, and biological properties of its components their interactions, and feedback processes that accounts for all or some of its known properties. The climate system can be represented by models of varying complexity; that is, for any one component or combination of components, a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions; the extent to which physical, chemical, or biological processes are explicitly represented; or the level at which empirical parametrizations are involved. (IPCC WG1)

Climate projection: A projection of the response of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasize that climate projections depend upon the emission/concentration/radiative forcing scenario used, which is based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized and are therefore subject to substantial uncertainty. (IPCC WG1)

Climate refugia: Areas that harbored species during past periods of changes in climate that could serve the same purpose in present and future climate change.

Climate resilience: The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change. (IPCC WG2)

Climate variability: Variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes (internal variability) within the climate system or to variations in natural or anthropogenic external forcing (external variability). (IPCC WG1)

Cloud forest: Moist, high-altitude forest characterized by dense understory growth; an abundance of ferns, mosses, orchids, and other plants on the trunks and branches of the trees; and a high incidence of low-level cloud cover.

Connectivity: A widely used term in conservation literature that in a freshwater context refers to the tendency for human infrastructure to fragment and disconnect habitats, thereby restricting the ability of species to move. The barriers may be within the water column or through some portion of the continuum of habitats between the headwaters of a river and its estuary, or between the river channel and floodplain.

Diadromous: Type of fish that uses both freshwater and marine habitats during its life cycle.

Dieback: A condition in woody plants in which peripheral parts are killed.

Ecological niche: The function an organism serves within an ecosystem.

Ecosystem services: Benefits that people obtain from ecosystems. These include provisioning services such as food, water, timber, and fiber; regulating services that affect climate, floods, disease, wastes, and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting services such as soil formation, photosynthesis, and nutrient cycling.

Ecosystem: A system of living organisms interacting with each other and their physical environment. The boundaries of what could be called an ecosystem are somewhat arbitrary, depending on the focus of interest or study. Thus, the extent of an ecosystem may range from very small spatial scales to, ultimately, the entire Earth.

Ecotone: A transitional zone between two communities that contains characteristic species from each.

Emissions scenario: A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., greenhouse gases, aerosols), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships. (IPCC WG1)

Endemism: The ecological state of being unique to a geographic area or continent.

Environmental flow: The amount of water needed in a river, wetland, or coastal zone to maintain the ecosystem and benefits to human communities.

Eutrophic: The condition of being rich in nutrients.

Eutrophication: A syndrome of ecosystemic responses to human activities that fertilize water bodies with nitrogen and phosphorus, often leading to changes in animal and plant populations and degradation of water and habitat quality.

Evapotranspiration: The transport of water into the atmosphere from surfaces, including soil, vegetation, and bodies of water.

Flow: The rate of water discharged from a source; expressed in volume with respect to time.

Groundwater: The supply of freshwater found beneath the Earth's surface (usually in aquifers).

Habitat fragmentation: The process by which isolated patches of habitat are created through land clearing, deforestation, or infrastructure development.

Headwaters: The place from which a river or stream originates.

Hydrograph: Chart that displays the change of a hydrologic variable over time.

Hydropattern: The mean pattern of water level fluctuation in a body of either flowing or still water; also a generic term that encompasses both flow regime and hydroperiod.

Hydroperiod: The mean pattern of water level fluctuation in a body of standing water such as a lake or wetland.

Kyoto Protocol: United Nations treaty that establishes a global cap-and-trade system for reducing greenhouse gas emissions.

New water: Largely derived from liquid precipitation — rain or frozen precipitation that melts very soon after falling.

Old water: Comes from reservoirs or "towers" of water that retain that water for long periods of time.

Oliogotrophic: The condition of being nutrient-deficient or nutrient-limited.

River basin: A portion of land drained by rivers and tributaries.

Runoff: Water that is not absorbed into the ground but instead flows across the land and eventually runs into streams and rivers.

Species richness: The number of species in a community, ecosystem, or another geographically defined area.

SRES: The storylines and associated population, GDP, and emissions scenarios associated with the Special Report on Emissions Scenarios and the resulting climate change and sea-level rise scenarios. Four families of socioeconomic scenarios (A1, A2, B1, and B2) represent different world futures in two distinct dimensions: a focus on economic versus environmental concerns, and global versus regional development patterns. (IPCC WG2)

Thermal stratification: The layering of a lake or body of water into distinct layers of different density caused by temperature differences.

Tidal zone: An area of land exposed to the air at low tide and submerged at high tide.

Tropical archipelago: A cluster of tropical islands.

Vulnerability: The extent to which a natural or social system is susceptible to sustaining damage from climate change. (Schneider et al., 2001)

Water cycle: The continuous exchange of water between the atmosphere and the areas on, above, and below the surfaces of the earth.

Water quality: Refers to how appropriate a particular ecosystem's water is for some use, whether biological or economical.

Water quantity: The water volume of a given ecosystem, which is controlled through the balance of inflows (precipitation, runoff, groundwater seepage) and outflows (water abstractions, evapotranspiration, natural outflows).

Water scarcity: Occurs when the demand for water is greater than the supply.

Water timing (water seasonality): The expected or average variation in water quantity over some period of time.

ACRONYMS

A1B:	A specific IPCC-defined emissions scenario
AAA:	Analytical and advisory activities
CAS:	Country Assistance Strategy
CCSP:	Climate Change Science Program (US)
CICOS:	Congo-Oubangui-Sangha International Commission
CSIRO:	Commonwealth Scientific and Industrial Research Organization (Australia)
CWRAS:	Country water resources assistance strategy
ENV:	Environment Department (World Bank)
ETW:	Energy, Transport, and Water Department
ETWWA:	Energy, Transport, and Water Department Water Anchor (World Bank)
FAR:	Fourth Assessment Report of the IPCC, published in 2007
GCMs:	Global circulation models or, alternatively, global climate models
GEF:	Global Environmental Facility
GTZ:	Deutsche Gesellschaft für Technische Zusammenarbeit (Germany)
HNB:	Hemwati Nandan Bahuguna Garhwal University
IPCC:	Intergovernmental Panel on Climate Change
IRBM:	Integrated River Basin Management
IUCN:	International Union for the Conservation of Nature
IWRM:	Integrated Water Resources Management
Lao PDR:	The People's Democratic Republic of Laos
LMB:	Lower Mekong basin
MRC:	Mekong River Commission
NAPA:	National Adaptation Programs of Action
OKACOM:	Permanent Okavango Water Commission
pH:	A chemical measure on a 14-point scale of relative acidity (below 7) or alkalinity (above 7); 7 is neutral
SD:	Statistical downscaling
SEA:	Strategic environmental assessment
SIWI:	Stockholm International Water Institute
SRES:	Special Report on Emissions Scenarios
TARB:	Tocantins-Araguaia River basin
TKK:	Helsinki University of Technology
UNFCCC:	United Nations Framework Convention on Climate Change
WBG:	World Bank Group
WCWSS:	Western Cape Water Supply Scheme
WG1, **WG2**:	Working Groups 1 and 2 of the IPCC assessment report series; WG1 focuses on the physical science behind anthropogenic climate change, and WG2 focuses on impacts, vulnerability, and adaptation
WRAS:	Watershed Restoration Action Strategy
WWF:	World Wildlife Fund

BIBLIOGRAPHY

Araujo, M. B., W. Thuiller, and R. G. Pearson, 2006. "Climate Warming and the Decline of Amphibians and Reptiles in Europe." ***Journal of Biogeography*** 33: 1712–28.

Arnell, N. W., 2004. "Climate Change and Global Water Resources: SRES Emissions and Socio-Economic Scenarios." ***Global Environmental Change*** 14: 31–52.

Barnett, T. P., J. C. Adams, and D. P. Lettenmaier, eds, 2005. "Potential Impacts of a Warming Climate on Water Availability in Snow-Dominated Regions." ***Nature*** 438: 303–309.

Bates, B. C., Z. W. Kundzewicz, S. Wu, and J. P. Palutikof, eds., 2008. ***Climate Change and Water***. Technical Paper of the Intergovernmental Panel on Climate Change. Geneva: IPCC Secretariat.

Cai, W. and T. Cowan, 2008. "Evidence of Impacts from Rising Temperature on Inflows to the Murray-Darling Basin." ***Geophysical Research Letters*** 35.

Capital International and Marsden Jacob Associates, 2006. ***Climate Change Impacts and Risk Management: A Guide for Business and Government***. Prepared for the Australian Greenhouse Office, Department of Environment and Heritage, Australian Government. Canberra: Australian Greenhouse Office, in the Department of the Environment and Heritage.

CCSP. ***Thresholds of Climate Change in Ecosystems. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research.*** Fagre, D. B., C. W. Charles, C. D. Allen, C. Birkeland, F. S. Chapin III, P. M. Groffman, G. R. Guntenspergen, A. K. Knapp, A. D. McGuire, P. J. Mulholland, D. P. C. Peters, D. D. Roby, and George Sugihara, 2009. US Geological Survey, Reston, VA.

CSIRO, 2008. ***Water Availability in the Murray-Darling Basin. A Report from CSIRO to the Australian Government.*** Canberra, CSIRO.

Daconto, G., 2001. "Siphandone Wetlands: An Overview," 7–19. In Daconto, G. (ed.), ***Siphandone Wetlands. Environmental Protection and Community Development in Siphandone Wetland Project***, CESVI, Bergamo, Italy.

Department for Environment, Food, and Rural Affairs, 2006. ***Economic Appraisal Supplementary Note to Operating Authorities — Climate Change Impacts***. Report No. FCDPAG3.

Environment Agency, 2007. ***Preparing for Climate Change Impacts on Freshwater Ecosystems (PRINCE): Literature Review and Proposed Methodology***. Report No. SC030300/SR, Literature Review. Bristol: Environment Agency Science Report, UK.

Epprecht, M., Minot, N., Dewina, R., Messerli, P., Heiniman, A., 2008. ***The Geography of Poverty and Inequality in the Lao PDR***, Washington, DC: IFPRI.

European Environment Agency, 2007. ***Climate Change and Water Adaptation Issues***. Technical Paper No. 2/2007. Copenhagen: European Environment Agency.

Evans, Warren. Director Environment Department, World Bank, SEA and IWRM — A World Bank Perspective presentation in Copenhagen, December 10, 2009.

Fischlin, Andreas, Guy F. Midgley, Jeff Price, Rik Leemans, Brij Gopal, Carol Turley, Mark Rounsevell, Pauline Dube, Juan Tarazona, and Andrei Velichko, 2007. "Ecosystems, Their Properties, Goods, and Services." In ***Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change***, edited by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. Van der Linden, and C. E. Hanson, 211–72. Cambridge: Cambridge University Press.

Giordano, M., Zhu, Z., Cai, X., Hong, S., Zhang, X., Xue, Y., 2004. ***Water management in the Yellow River Basin: Background, Current Critical Issues and Future Research Needs***. Comprehensive Assessment Research Report 3. Colombo, Sri Lanka: Comprehensive Assessment Secretariat.

GPPN, and SIWI, 2009. ***Guide to Water and Climate Change Adaptation in Relation to UNFCCC Negotiations***. Report. London: GPPN.

Greater London Authority (GLA), 2005. ***Adapting to Climate Change: A Checklist for Development***. Report. London: London Climate Change Partnership.

Hansen, L. J., and M. Hiller, 2007. ***Defending Nature against Climate Change: Adapting Conservation in WWF's Priority Ecoregions***. Report. Washington, DC: WWF Climate Change Program.

Hansen, L., J. Hoffman, and J. Biringer, 2003. ***Buying Time: A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems***. Report. Washington, DC: WWF.

Heino, J., R. Virkkala, and H. Toivonen, 2009. "Climate Change and Freshwater Biodiversity: Detected Patterns, Future Trends and Adaptations in Northern Regions." ***Biol Rev Camb Philos Soc.*** 84, no. 1: 39–54.

Hellmuth, M. E., A. Moorhead, M. C. Thomson, and J. Williams, eds, 2007. ***Climate Risk Management in Africa: Learning from Practice***. Report. New York: International Research Institute for Climate and Society, Columbia University.

Hirji, R., Johnson, P., Maro, P. and Matiza Chiuta, T., eds, 2005. ***Defining and Mainstreaming Environmental Sustainability in Water Resources Management in Southern Africa***, SADC, IUCN, SARDC, World Bank: Maseru/Harare/Washington, DC.

Hirji, R., and R. Davis, 2009a. ***Environmental Flows in Water Resources Policies, Plans, and Projects — Findings and Recommendations***. Environment and Development Report. Washington, DC: World Bank.

Hirji R. and R. Davis, 2009b. ***Strategic Environmental Assessment. Improving Water Resources Governance and Decision Making***. Water Sector Board Discussion Paper 12. Washington, DC: World Bank.

International Water Management Institute, 2007. ***A Comprehensive Assessment of Water Management in Agriculture***. Report. London: Earthscan.

ILEC, 2005. ***Managing Lakes and Their Basins for Sustainable Use: A Report for Lake Basin Managers and Stakeholders***, International Lake Environmental Committee Foundation: Kusatsu, Japan.

IPCC, 2007. ***Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change***. Report. Geneva: IPCC.

IUCN, 2008. ***An Integrated Assessment of the Biodiversity, Livelihood and Economic Implications of the Proposed Special Management Zones in the Stung Treng Ramsar Site, Cambodia***. Vientiane: IUCN.

IUCN. 2008b. ***Siphandone Under Threat,*** Vientiane: IUCN.

Krchnak, Karin, Brian Richter, and Gregory Thomas, 2009. ***Integrating Environmental Flows into Hydropower Dam Planning, Design, and Operations***. World Bank Water Working Notes No. 22. Washington, DC: World Bank.

Kura, Y., C. Revenga, E. Hoshino and G. Mock, 2004. ***Fishing for Answers***, World Resources Institute, Washington, DC.

Layke, Christian. 2009. ***Measuring Nature's Benefits: A Preliminary Roadmap for Improving Ecosystem Service Indicators***, WRI Working Paper. World Resources Institute, Washington, DC. Available online at http://www.wri.org/project/ecosystem-service-indicators.

Ledec, G., and J. Quintero, 2003**. *Good Dams and Bad Dams: Environmental Criteria for Site Selection of Hydroelectric Projects***, Latin America and Caribbean Region Sustainable Development Working Paper 16, World Bank.

Matthews, J., A. Aldous, and A. J. Wickel, 2009. "Managing Water in a Shifting Climate." ***Journal of the American Water Works Association***, August, 28–30.

Matthews, J., and T. Le Quesne, 2009. ***Adapting Water Management: A Primer on Coping with Climate Change***. Report. Vol. 3. Godalming: WWF-UK.

Matthews, J., and A. J. Wickel, 2009. "Embracing Uncertainty in Freshwater Climate Change Adaptation: A Natural History Approach." ***Climate & Development*** 1, 269–79.

Millennium Assessment, 2005. ***Ecosystems and Human Well-being: Current State and Trends: Findings of the Condition and Trends Working Group***, edited by Rashid Hassan, Robert Scholes, Neville Ash.

Miller, K., and D. Yates, 2006. ***Climate Change and Water Resources: A Primer for Municipal Water Providers***. Report. Denver: AWWA Research Foundation.

MOEF. Ministry of Environment and Forests Notification, ***Gazette of India: Extraordinary***, February 20, 2009, Government of India Press: New Delhi.

NWC, 2009. ***Australian Water Reform 2009: Second Biennial Assessment of Progress in Implementation of the National Water Initiative***. Canberra, National Water Commission.

O'Reilly, C., Simone R. Alin, Pierre-Denis Plisnier, Andrew S. Cohen, and Brent A. McKee, 2003. "Climate Change Decreases Aquatic Ecosystem Productivity of Lake Tanganyika, Africa." ***Nature*** (424) 766–68.

Heyns, P.S.V.H., G. Gabaake, and I. Pinheiro, 2003. "Cooperation in the Okavango River Basin: The OKACOM Perspective." In ***Transboundary Rivers, Sovereignty and Development: Hydropolitical Drivers in the Okavango River Basin***, edited by A.R. Turton, P.J. Ashton, and T.E. Cloete. Pretoria, South Africa/Geneva, Switzerland: AWIRU/Green Cross.

Poff, N. L., M. M. Brinson, and J. W. Day, 2002. ***Aquatic Ecosystems and Global Climate Change***. Arlington, VA: Pew Center on Global Climate Change.

Pounds, J. A., M. R. Bustamante, L. A. Coloma, J. A. Consuegra, M. P. L. Fogden, P. N. Foster, E. La Marca, K. L. Masters, A. Merino-Viteri, R. Puschendorf, S. R. Ron, G. A. Sánchez-Azofeifa, C. J. Still, and B. E. Young, 2006. "Widespread Amphibian Extinctions from Epidemic Disease Driven by Global Warming." ***Nature*** 439: 161–67.

Quintero, J., 2007. ***Mainstreaming Conservation in Infrastructure Projects — Case Studies from Latin America,*** World Bank: Washington, DC.

Rockström, J., M. Lannerstad, and M. Falkenmark, 2007. "Assessing the Water Challenges of a New Green Revolution in Developing Countries." ***Proceedings of the National Academy of Sciences of the United States of America*** 104: 6253–60.

Rosenzweig, C., C. Casassa, D. J. Karoly, Anton Imeson, Chunzhen Liu, Annette Menzel, Samuel Rawlins, Terry L. Root, Bernard Seguin, and Piotr Tryjanowski, 2007. "Assessment of observed changes and responses in natural and managed systems." In ***Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change***, edited by Lucka Kajfe-Bogataj, Jan Pretel, and Andrew Watkinson, 79–131. Cambridge: Cambridge University Press.

Scholze, M., W. Knorr, N. W. Arnell, and I. C. Prentice, 2006. "A Climate Change Risk Analysis for World Ecosystems." ***Proceedings of the National Academy of Sciences of the United States of America*** 103: 13116–20.

SEACI, 2008. Media release. May 1, 2008. Global Warming Linked to Rainfall Decline in South-East Australia. Canberra, South-Eastern Australia Climate Initiative.

Secretariat of the Convention on Biological Diversity, 2010. ***Global Biodiversity Outlook 3***.

Speed, R., May 2010. Personal comment.

Sverdrup-Jensen, S., 2002. ***Fisheries in the Lower Mekong Basin: Status and Perspectives***. MRC Technical Paper No. 6, Mekong River Commission, Phnom Penh.

Timbal, B., 2009. ***Centre for Australian Weather and Climate Research (Research Letters)*** 2: 4–11.

Try, T., and Chambers, M., 2006. ***Situation Analysis: Stung Treng Province, Cambodia***. Vientiane: Mekong Wetlands Biodiversity Conservation and Sustainable Use Program.

United Kingdom. Department for Environment, Food and Rural Affairs, 2009. ***FCDPAG3 Economic Appraisal Supplementary Note to Operating Authorities — Climate Change Impacts.*** http://www.sdcg.org.uk/Climate-change-update.pdf.

United Kingdom. Greater London Authority. London Climate Change Partnership, 2009. ***Adapting to Climate Change: A Checklist for Development.*** http://www.london.gov.uk/lccp/publications/development.jsp.

United Nations Framework Convention on Climate Change, 2008. ***Compendium on Methods and Tools to Evaluate Impacts of, and Vulnerability and Adaptation to, Climate Change***. Report. Nairobi: United Nations Framework Convention on Climate Change.

Vos, C. C., P. Berry, P. Opdam, H. Baveco, B. Nijhof, J. O'Hanley, C. Bell, and H. Kuipers, 2008. "Adapting Landscapes to Climate Change: Examples of Climate Proof Ecosystem Networks and Priority Adaptation Zones." ***Journal of Applied Ecology*** 45: 1722–31.

Wilby, R. L., J. Troni, Y. Biot, et al, 2009. "A Review of Climate Risk Information for Adaptation and Development Planning." ***International Journal of Climatology*** 10, no. 1002.

Willows, R. I., and R. K. Connell, eds, 2003. ***Climate Adaptation: Risk, Uncertainty and Decision-Making***. UKCIP Technical Report. Oxford: UKCIP.

WMO. Report No. WMO-No. 986. http://www.wmo.ch/pages/prog/www/StatusReport.html.

World Bank, 2005. ***Pakistan Country Water Resources Assistance Strategy: Water Economy: Running Dry.*** World Bank South Asia Region, Agriculture and Rural Development Unit.

World Bank, 2008. ***Development and Climate Change: A Strategic Framework for the World Bank Group***. Report. Washington, DC: World Bank.

World Bank, 2009. ***Water and Climate Change: Understanding the Risks and Making Climate-Smart Investment Decisions***. Washington, DC: Energy, Transportation, and Water Department, World Bank.

World Bank, 2010a. ***Convenient Solutions to an Inconvenient Truth: Ecosystem-based Approaches to Climate Change***, Environment Department, World Bank.

World Bank, 2010b. ***World Development Report — Development and Climate Change***, World Bank.

World Bank, 2010c. ***Sustaining Water for All under a Changing Climate — World Bank Group Implementation Progress Report of the Water Resources Sector Strategy.***

Wrona, F. J., J. D. Prowse, J. E. Reist, et al, 2006. "Climate Change Effects on Aquatic Biota, Ecosystem Structure and Function." ***Ambio*** 35: 359–69.

WWC, IUCN, and CPWC, 2009. ***Don't Stick Your Head in the Sand! Towards a Framework for Climate-Proofing***. Report. WWC.

WWF-UK, 2008. ***Water for Life: Lessons for Climate Change Adaptation from Better Management of Rivers for People and Nature***. Report. Godalming: WWF-UK.

WWF. ***Case Studies in Flowing Forward: Supporting Freshwater Ecosystem Adaptation in Water Resources, Biodiversity Conservation and Climate Change Adaptation Activities: Case Study Annex***, John H. Matthews, Tom Le Quesne, and Constantin Von der Heyden (authors), at press.