November 2009

WATER AND CLIMATE CHANGE:

UNDERSTANDING THE RISKS AND MAKING CLIMATE-SMART INVESTMENT DECISIONS

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THE WORLD BANK

Water Sector Board

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FOREWORD

The IPCC's Fourth Assessment Report (2007) and other technical studies have 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 on human societies and ecosystems. Each Bank region is likely to face a unique set of water-related climate change challenges, deriving from such impacts as accelerated glacier melt; altered precipitation, runoff and recharge patterns and rates; extreme floods and droughts; water quality changes; saltwater intrusion in coastal aquifers; and changes in water uses. In this context, the 2010 World Development Report emphasizes that water will have to be used more efficiently, that climate-smart practices will have to be adopted and that countries will need to co-operate to manage shared water resources.

Potential adaptation strategies to the impacts of climate change on water resources have become central to the dialogue on water policy reforms and investment programs with client countries. In order to complement regional efforts already underway, and to support future regional initiatives, the Water Anchor in the Energy, Transport and Water department (ETW) in the Sustainable Development Vice Presidency has undertaken a two-year analytical work on Climate Change and Water.

The main objective is to provide analytical, intellectual and strategic assistance to the regions for incorporating adaptation to climate variability and change in their work programs. The report focuses on water and water-related issues and investments. A particular focus of the work is on reducing the vulnerability of water sector investments to the impacts of climate change. Furthermore, the report provides a first version of a tool that can be used to assess exposure and screen the investment portfolio on a regional basis.

This ETW Anchor Flagship consists of this main report and a series of supporting technical reports and papers reflecting the output of a two year effort. The series includes a synthesis of the state-of-the-art of the science as related to climate and hydrologic cycle; an analysis of climate change impacts on groundwater resources and adaptation options; a review of the Bank's current water investment portfolio with regards to the extent to which climate change is considered at the project design level; and an evaluation of the exposure of the World Bank water sector investments. Also included in this Flagship product is a menu of adaptation options for increased robustness and resiliency of water systems to climate variability/change, and a framework for risk-based analysis for water investment planning. It is hoped that this work will help enhance knowledge and understanding of both Bank staff and client country professionals for making better-informed decisions regarding water investments.

Jamal Saghir
Director, Energy, Transport and Water
Chair, Water Sector Board

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This report provides an overview of the series of reports and documents prepared as part of the Flagship product of the Water Anchor of the Energy, Transport, and Water Department. The effort was led by Vahid Alavian under the overall guidance of Abel Mejia and Jamal Saghir. The core water and climate change team responsible for this work includes Halla Maher Qaddumi, Eric Dickson, Sylvia Michele Diez, Alexander V. Danilenko, Rafik Fatehali Hirji, Gabrielle Puz, Carolina Pizarro, Michael Jacobsen, all from the Water Anchor and Brian Blankespoor from DEC Research Group.

Significant contributions were made—through preparation of technical reports, background notes, thematic inputs, and model simulation—by Professor Kenneth Strzepek and his climate change team at the University of Colorado and Massachusetts Institute of Technology (MIT); by Stratus Consulting, particularly Joel Smith and his team; by Nick Pansic and his team at Montgomery Watson Harza (MWH); and by Sinclair Knight Merz (SKM), particularly Rick Evans and his team. These consultants effectively served as partners and members of the water and climate change team at the Water Anchor during the course of this work.

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Disclaimer

ABBREVIATIONS AND ACRONYMS

AAA	Advisory and analytic activities
ACRA	Country Adaptation to Climate Risk Assessment
AFR	Africa Region
AOGCM	Atmospheric-Ocean General Circulation Model
CAS	Country Assistance Strategy
CC	Climate Change
CDM	Clean Development Mechanism
CEIF	Clean Energy for Development Investment Framework
CF	Carbon Finance
COP	Conference of the Parties
CO_2	Carbon dioxide
CPIA	Country Policy and Institutional Assessment
DEC	Development Economics Department
DPL	Development policy lending
EAP	East Asia and the Pacific
ECA	Europe and Central Asia
ENSO	El Niño-Southern Oscillation
ESMAP	Energy Sector Management Assistance Program
4AR	Fourth Assessment Report (IPCC)
FAR	First Assessment Report (IPCC)
GCM	General Circulation Model
GDP	Gross domestic product
GEF	Global Environment Facility
GHG	Greenhouse gases
GPG	Global public good
IBRD	International Bank for Reconstruction and Development
IDA	International Development Association
IFC	International Finance Corporation
IPCC	Intergovernmental Panel on Climate Change
km	Kilometer
LCR	Latin America and the Caribbean
MDG	Millennium Development Goals
MIGA	Multilateral Investment Guarantee Agency
MNA	Middle East and North Africa
MOSES	Met Office Surface Exchange Scheme
NAO	North Atlantic Oscillation
NAPA	National Adaptation Programme of Action
ODA	Official development assistance
PCMDI	Program for Climate Model Diagnostics and Intercomparison
PPIAF	Public-Private Infrastructure Advisory Facility
ppm	parts per million
PPP	Public-Private Partnership
PRSP	Poverty Reduction Strategy Paper
PSDI	Palmer Drought Severity Index
RCM	Regional Climate Model
SAR	Second Assessment Report (IPCC)
SAR	South Asia Reigon

SCCF	Special Climate Change Fund
SD	Statistical Downscaling
SEA	Strategic Environmental Assessment
SKM	Sinclair Knight Merz
SRES	Special Report on Emissions Scenarios
SSA	Sub-Saharan Africa
SWAp	Sectorwide approach
TA	Technical assistance
TAR	Third Assessment Report (IPCC)
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WBG	World Bank Group
WDR	World Development Report
WWF	World Wildlife Fund

EXECUTIVE SUMMARY

Introduction

Climate change is real, and taking prudent measures to plan for and adapt to climate change must become an integral part of the Bank's water practice. There is now ample evidence that increased hydrologic variability and change in climate has and will continue have a profound impact on the water sector through the hydrologic cycle, water availability, water demand, and water allocation at the global, regional, basin, and local levels. Many economies are at risk of significant episodic shocks and worsened chronic water scarcity and security. This can have direct and severe ramifications on the economy, poverty, public health and ecosystem viability. This report documents the results of the first two years of a sustained effort at the Energy, Transport, and Water Department of the World Bank to understand the risks of climate change to the water sector and to identify ways to manage these risks for better and climate-smart investment decisions.

This report and the analytical work leading to it are focused on key topics related to the impact of climate change on the water cycle and water investments. Specifically, the topics addressed are: a better understanding of the science and uncertainties of climate change projections as related to the hydrologic cycle; translating the climate projections to projection of hydrologic indicators useful in policy and planning of water investments; a review of the World Bank water portfolio for climate change content and adaptation options considered; and finally an examination of the exposure of the portfolio to climate-induced changes in hydrologic drivers if the active portfolio were placed in 2030 and 2050. Special care has been taken to provide the reader with an understanding of the critical assumptions behind the climate change projections, hydrologic models, and application of the science in practice. Cautionary notes are also provided where common misunderstandings, misconceptions, or pitfalls may occur in making use of the climate change information in making investment decisions. The results reported herein focus on the impact of climate change on the water cycle as the primary driver of the water sector and are meant for use at the policy and planning level in making investment decisions. The findings here are not intended for detailed project design applications. With the best available knowledge on climate change and water as the foundation, economics of adaptation, social, poverty, and environmental aspects can now be addressed and are on the agenda for the follow up work.

The context

Climate change is a development issue for the Bank and its clients with significant implications in the water sector. WBG clients, by virtue of their geographic location and often low coping capacity, are among the most affected. The Bank's 2007 report *IDA and Climate Change: Making Climate Action Work for Development* provides compelling evidence that the distribution of major climate-related risks around the world is skewed against poor countries. The Bank's 2009 Development and Climate Change Strategic Framework (DCCSF) (World Bank, 2008a) asserts that climate change is a development issue, among others, and recognizes the water sector as one that will be heavily impacted by climate change. The 2010 World Development Report focuses, among other factors, on the land and water interface for managing competing demands and creating new opportunities for climate-smart development. Many client countries in partnership with the World Bank Group have begun to take action to adapt their water sector to implications of climate change and resulting hydrologic impacts. This process is supported by analytical and advisory assistance on water and climate change carried out by Regional Units, as well as the Water Anchor. Incorporating climate change in the portfolio has been steadily increasing in response to client demands. A number of stand-alone climate change projects have also been financed through various grant and lending instruments and they are increasing. The recent financial crisis, as well as the food and fuel price crises put stress on many economies and sectors, including water. However, this provides a unique opportunity to use the Bank's increased engagement to close the financial gap for thinking and investing smartly by taking into account the wider climate change issues.

Each World Bank region, even each country and each river basin face a unique set of climate change-related water challenges. Depending on the hydrologic regime, regional and sub-regional hydrology and climate variability have a direct, but differential, impact on the various water use areas. Floods/droughts, water availability/allocation and water quality management are affected by climate change and have an upward linkage to the economy. Indirect and second order impacts can also be significant in water storage lakes and reservoirs; agricultural production; navigation; and the increased vulnerability of ecosystems. Many client countries are particularly vulnerable to the impacts of hydrologic variability and climate change given weak institutions and institutional capacity, high levels of poverty, insufficient stock of water management and services infrastructure and dependence of the rural economy on agriculture. The gap between availability of water storage infrastructure in developed and developing countries is wide. Climate change may increase or reduce the need for water storage infrastructure depending on its impact on the hydrologic cycle. One key question concerns the strategies that need to be put in place to mitigate the negative impacts of climate change. Potential adaptation strategies to the impacts of climate change on water resources have become central to the dialogue on water policy reforms and investment programs with client countries.

Conventional interventions are necessary but not sufficient. Water practitioners have long coped with and designed for variability in hydrology. Consequently, numerous examples of adaptation to hydrological variability and extreme events exist in the water sector. Implementing the "good practices" more widely (e.g., efficient irrigation technologies, water harvesting, increased sub-surface storage, etc.) would go a long way in confronting the climate change challenge. Adapting to climate change must continue to build on conventional interventions while addressing the immediate challenges, but must make a major shift in thinking, planning and designing water investments of the future. New approaches in technology and management, as well as the development of flexible and "smart" systems that can be operated to anticipate and react to changing circumstances must be developed, particularly in light of uncertainties in projected impacts. New design standards and criteria will also need to be developed for a changed hydrology characterized by increased variability and uncertainty. Guidelines for mainstreaming adaptation into project design must take all of these aspects into account if they are to be effective.

This report contributes to the World Bank agenda on climate change and more specifically, informs the water sector investments on climate issues and climate-smart adaptation options. Using the existing knowledge and additional analysis commissioned by the World Bank Water Anchor, the report illustrates that climate change is affecting the hydrologic cycle and the projected future hydrology will have a direct impact on the water resources base—availability, usage, and management. Depending on the type of the water investment, this impact can be positive, negative, or neutral. The report addresses the stress on and vulnerability of the water systems through use of reliability, resilience, and robustness as the key indicators of sensitivity of water systems for climate induced failure. Current practices in the sector are examined in order to better understand the state-of-the-science for incorporating current and future variability and change in hydrology and climate in the Bank's portfolio for project planning and design. New and innovative practices taking into account adaptation options for water systems and risk-based decision making in water investments are reviewed and assessed for application to investments in infrastructure. The climate change dimension is placed within the context of the impact of other factors (within and outside the sector) such as population growth (and associated increase in demand) and land management (particularly as related to water), which in some cases may be far more significant and critical than that of climate change in some parts of the world. Finally, recommendations for a progressive agenda on water and climate change are made.

Climate change, hydrologic cycle, and water

Hydrologic cycle as the key external driver of the water cycle is accelerating due to climate change. Projected increases in global temperatures are associated with changes in the hydrologic cycle, including increased atmospheric water vapor, changes in precipitation patterns (frequency and intensity), as well as changes in groundwater and soil moisture. These changes

Key Variables	***Observed Trends***	***Projections for 21st Century***
Precipitation	Trend is unclear. General increases in precipitation over land from 30°N to 85°N. Notable decreases from 10°S to 30°N.	Increase (about 2%/°C) in total precipitation. High latitude areas generally projected to increase. Many low to mid-latitude areas projected to decrease. Changes at the regional scale vary.
Atmospheric water vapor content	Increasing in lower atmosphere (lower troposphere; about 1%/decade) in specific humidity; little change in relative humidity	Increasing
Intensity of precipitation	Disproportionate increase in volume of precipitation in heavy or extreme precipitation events	Increasing (about 7%/°C)
Droughts	Drought, as measured by the Palmer Drought Severity Index, increased in the 20th Century, although some areas became wetter	Increasing in many areas, particularly lower latitudes. Decreasing in many high latitude areas. Patterns are complex.
Tropical cyclones	Increases in intensity, particularly in North Pacific, Indian Ocean, and Southwest Pacific	Increase in intensity. Changes in frequency and track are uncertain
Glaciers and snow cover	Decrease in mass of glaciers, but not in all regions. Decrease in snow cover in regions in the northern Hemisphere. Earlier peak runoff from glacier and snowmelt.	Continued decrease in glacial mass and snow cover
Sea level	Increased about 0.2 meters over the 20th century. A rise equivalent to 0.3 meters per century was recorded since the early 1990s, but it is not clear if this is an acceleration of long term sea level rise	IPCC projects 0.2 to 0.6 meters by 2100, but upper end could be much higher.

Source: Derived from IPCC, 2007a; Kevin Trenberth, National Center for Atmospheric Research. Personal Communication. May 19, 2008; Trenberth et al., 2003.

are often referred to as an *intensification and acceleration of the hydrologic cycle*. The result of hydrologic change and increased variability is shorter periods of more intense rainfall, and longer warmer dryer periods. The table below summarizes the observed trends and projections for the 21st century of key hydrologic variables. Increase in variability and intensification of hydrologic processes is evident.

The impact of climate change varies with hydrology/climate regime and water use sectors. In some climatic regions (such as parts of LCR and ECA), glacier and snowmelt define hydrology while in other parts of the world, precipitation is the driving factor (for example much of AFR). The impact of climate change on snow-driven hydrology is quite different from rainfall-driven hydrology. In *snow-driven hydrology*, changes in the pattern of precipitation and the associated acceleration of snow and glacier melt from rising temperatures are projected to significantly affect runoff and, consequently, water available for human consumption, agriculture and energy generation. Changes in the timing of runoff can cause increased flooding, failure of storage infrastructure, landslides, and loss of surface soil. In systems fed by snowmelt it is generally the shape (volume) and timing of the runoff that matters. Hydrologic variability—while always present—is more predictable and so less significant. In contrast, in *rainfall-driven hydrology*, flood and drought cycles are much less predictable and their magnitude (severity) has a significant impact on water availability (quantity, quality, and timing) for water supply and sanitation, agricultural production (yield, growing season), energy (hydropower), and environmental sustainability. Climate change will exacerbate the uncertainty and severity of hydrologic variability. Regardless of the hydrologic regime, the impact of hydrologic variability and climate change on coastal regions (particularly in EAP, SAR and the Caribbean) is expected to be significant through sea level rise on the sea-side and increased flooding from the land-side.

Climate change could profoundly alter future patterns of both water availability and use, thereby increasing global levels of water stress. Direct effects of climate change on water resources and availability as a result of changes in hydrology is shown above. Less is known about the impacts of climate change on groundwater availability, including interactions with surface water. There is also relatively little information on the impact on water quality and aquatic systems. The potential changes in water availability and use may aggravate global 'water stress'. Most studies have found that levels of water stress will increase, although there are significant differences in estimates. Arnell (2004)—who accounts for population growth and the impact of climate change—found that the number of people projected to experience an increase in water stress is between 0.4 to 1.7 billion in the 2020s and between 1 and 2.7 billion in the 2050s (using the A2 population scenario for the 2050s). When environmental flow needs are incorporated—that is, the amount of water required to sustain a functioning ecosystem—the degree of water stress is projected to increase even further (Smakhtin et al, 2003).

Future water availability and use will also depend on non-climatic factors. Climate change is only one of many factors that will determine future patterns of water availability and use. In the absence of policy changes, non-climatic factors are likely to aggravate or attenuate the adverse effects of climate change on water availability and quality, as well as have a significant influence on water demand. Population growth and economic development will play a dominant role. Non-climatic impacts could be generated through many realms—from population growth, migration and income to technologies and infrastructure to land-use patterns and agricultural activities/irrigation. Such non-climatic drivers could dwarf the impacts attributed to climate change alone. Changes in policies, legislation and management could induce additional and substantial effects on water demand and water availability (quantity and quality), in a positive or negative direction.

Water sector is highly exposed to climate change with implication beyond the sector

The impacts of a changing climate will be felt in developed and developing countries alike. However, many parts of the developing world are particularly vulnerable. Vulnerability to climate change has been defined by IPCC as the degree to which geophysical, biological and socioeconomic systems are susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. It is a function of, amongst others, the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity. Within the water sector, a number of additional factors make many developing countries—and the poorest within them—particularly vulnerable to the potentially adverse impacts of climate change. These include weak institutions and limited institutional capacity, high levels of poverty, insufficient stock of water management and services infrastructure, lack of access to technology and capital to invest in risk reduction, and dependence on climate-sensitive sectors such as agriculture, forestry and fisheries.

Water investments are particularly vulnerable to impacts of climate change through the hydrologic drivers. Climatic impacts will have significant consequences on investments in water systems (or infrastructure) associated both with delivering water services and with managing water. Water systems for delivering water services include irrigation; urban water, sanitation and drainage; rural water and sanitation; and ports and navigation. Systems for managing water resources include those for delivery of bulk irrigation, watersheds, and water resources broadly, as well as multi-purpose systems (including hydropower) and flood control. For example, in urban environments, more heavy rainfall events could overload the capacity of storm drain systems and water and wastewater treatment facilities; sea level rise could lead to salinisation of water supplies from coastal aquifers. Climate change could increase irrigation demand due to the combination of decreased rainfall and increased evapotranspiration, placing additional pressure on irrigation systems that are in many cases already under performing. Changes in river flows have a direct impact on hydropower generation. Soil erosion from increased rainfall intensity could affect watershed sustainability and lead to sedimentation in reservoirs, impacting on the operation of multi-purpose facilities. Extreme variability and/or reduced supplies could stretch the infrastructural and institutional limits of systems that manage water across sectors and even national boundaries. The term 'system' and 'infrastructure' are used interchangeably in this report to capture all elements—physical infrastructure, management institutions, and financial aspects—that contribute to the performance of the intended function of water investments.

The extent to which each water system will be impacted by climate change will depend on its degree of vulnerability, including internal capacity to adapt. However, the potential impacts of climate change are real, and may extend far beyond the water sector. For example, pressure on water supply and sanitation facilities could have a wide range of adverse effects on human health. Reduced availability of water for irrigation could threaten food security, rural development, and the economies of countries that are largely dependent on the agricultural sector. Reduced water for hydropower generation (or increased fluctuations in river flows) could decrease electricity grid stability and reliability, with consequent effects on the economy. Managing sedimentation (e.g., through flushing) could affect the timing, supply and quality of water to the various sectors served by a multi-purpose system, with impacts felt in the larger economy. In the worst case, competition over limited water resources across sectors and nations could worsen hostility and mistrust, and increase conflicts over water.

Water-dependent sectors are affected by the impact of climate change on the water sector. In most countries, water use has increased in recent decades. Sectoral water use patterns can be expected to continue to change over time in response to non-climatic drivers, in addition to water resource management and delivery systems. This includes not only infrastructure and technology, but also institutions that govern water use within sectors (e.g., water pricing), amongst sectors (e.g., water trading), and even across national boundaries (e.g., transboundary river basin agreements). In the future, climate change could also impact water using sectors, affecting both the amount and/or quality desired (on the demand side) and/or the extent to which demands are met (on the supply/availability side). It is important to emphasize that changes in variability could be as important as changes in long-term averages, particularly if water is not withdrawn from groundwater bodies or reservoirs.

International basins can be at risk due to climate change. Over 270 international rivers are shared by some 90% of the world's nations and territories. Transboundary river basins and shared rivers present both challenges and opportunities for cooperation and growth. Developed economies, in Europe and North America, have in most cases achieved a relative equilibrium in managing transboundary basins for best return on hydrology through transboundary institutional arrangements, including treaty regimes dealing with issues of river infrastructure and the quantity and quality of water flows, as well as infrastructure to manage variability and extreme events. Increasingly, cooperative efforts are focusing on the sharing of benefits, rather than water. The developing economies sharing river basins remain challenged by lack of weak institutional arrangements and inadequate infrastructure for optimum benefit. Regardless of the level of economic development, climate change poses a threat to transboundary basins. Evidence suggests that the challenges and conflicts among the riparian states depend on the degree of variability and uncertainty associated with the resource availability. Projected changes in water resources variability due to climate change can impact the water balance and consequently the hydropolitical balance in transboundary basins. Administrative instruments for transboundary basins, such as treaties and agreements should be reviewed for impact of climate change with adaptation measures explored and negotiated in advance.

The current financial crisis and various sector crises have and will continue to impact financing of adaptation to climate change. A theme that has been emphasized throughout this report is that climate change is not the only—or even the primary—factor exerting stress on the water sector, and by extension societies, economies, and the environment. The current financial crisis and the sector crises (e.g., rising food prices, energy cost) have forced many governments in developing countries to defer urgent operation and maintenance, as well as water investment needs. In the near- to medium-term, the situation is expected to worsen unless investment funds are channeled to the water sector. Here, a combination of the new financial and climate change architectures such as the Vulnerability Fund, the Climate Investment Fund, and other mechanisms to alleviate the investment bottle neck should be made available to the client Bank countries. Viewed in the long term, the current financial crisis and the stimulus packages to respond to this crisis can be designed to take into account the wider risk of climate change in the recovery and rebuilding process.

World Bank water investments and climate change

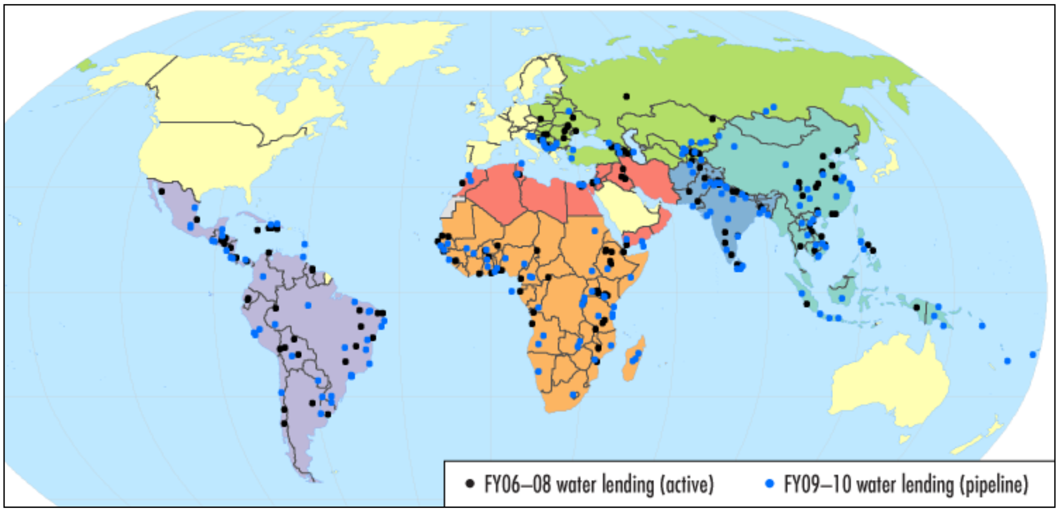
Climate change poses risk to World Bank investments in the water sector. A review of the water portfolio was undertaken to understand the composition of the Bank water investments and their exposure to climate change. Bank's investments in the water sector over the period fiscal years 2006–2010 are reviewed for class of investment—water services delivery or water resources management—and climate change content of the project. This particular period offers sufficient number of approved and pipeline projects for review during a time frame that climate change is high in the Bank's agenda. Additionally, exposure of Bank's water investment to current hydrologic variability and future climate change were assessed using hydrology projections at a scale and resolution useful in water planning and design.

The water portfolio reviewed consists of 191 projects approved in 83 countries during FY06–08 for net commitments of $8.8 billion. The regions that invested the most in water relative to their total regional investment are MNA (14%) and SAR (14%) and the region that invested the least is LCR (8%). The share of water lending relative to the overall World Bank's investments increased from 8% in FY06 to 12% in FY08. The pipeline of projects for FY09–10 consists of 220 projects corresponding to a volume of US$11.3 billion. It should be noted that not all the projects in the pipeline will be approved by end of FY10. The two figures below show these investments by geographic location, volume, and type—services/resource management.

The water portfolio is dominated by projects that primarily deliver water services. For the FY06–08 period lending for water services consist of 70% of the lending volume for 63% of the projects. The largest investment in water services systems is in EAP ($1,327 million), SAR ($1,241 million) and AFR ($1,128 million) regions. For this period, highest lending in water resources is in AFR ($926 million), followed by SAR ($703 million) and EAP ($364 million). Implication of climate change on these investments would be different as the driving hydrologic conditions are different.

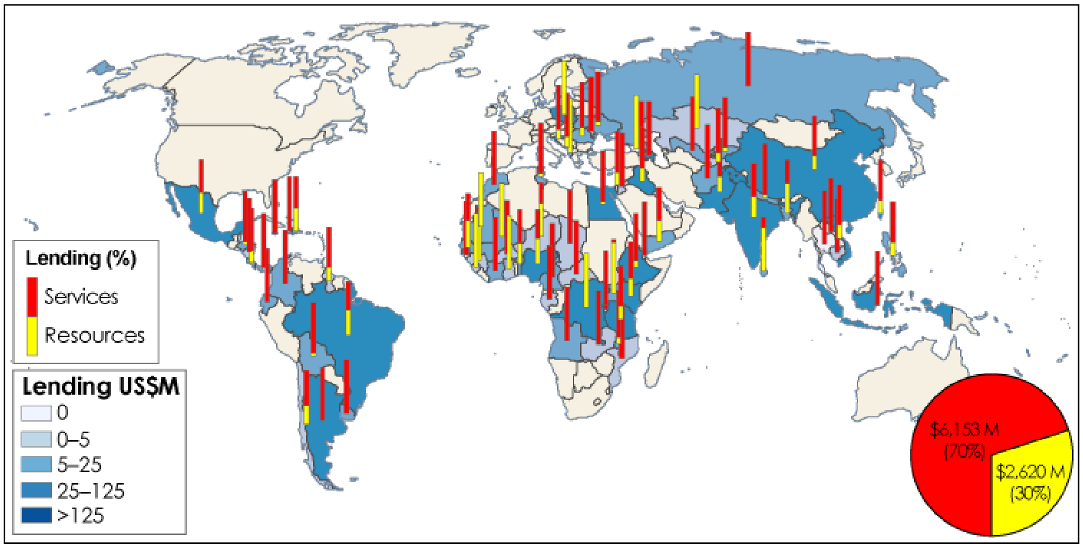
Review of the content of the portfolio suggests an increasing level of attention to climate change. The review of water projects for inclusion of mitigation and adaptation measures shows that out of 191 active projects approved in FY06–08, 35% (67 projects) considered strategies

Distribution of World Bank water projects for FY06–08 (active) and FY09–10 (pipeline)



Source: World Bank, 2009.

Water investments by volume and category (services/resource management)



Source: World Bank, 2009.

to reduce the impacts of climate variability and change, including adaptation and/or mitigation measures. Of the 67 projects with some strategy, 58% are related to adaptation, 31% related to mitigation and 10% related to both. The water sector projects are primarily focused on adaptation. For the active portfolio, 20% of the projects addressed climate variability and change through adaptation measures. Of the 20% of projects taking adaptation measures, it is important to note that these measures address, for the most part, strategies to reduce vulnerability to climate variability rather than considering the long-term effects of climate change. Of the total number of projects at the regional level, LCR had the largest portfolio with possible adaptation measures (28%) followed by SAR (25%) and MNA (25%). Pipeline shows an increased attention to the adaptation agenda for most regions. Overall, there is clearly a higher level of awareness among the Bank and client countries towards climate change and climate variability issues.

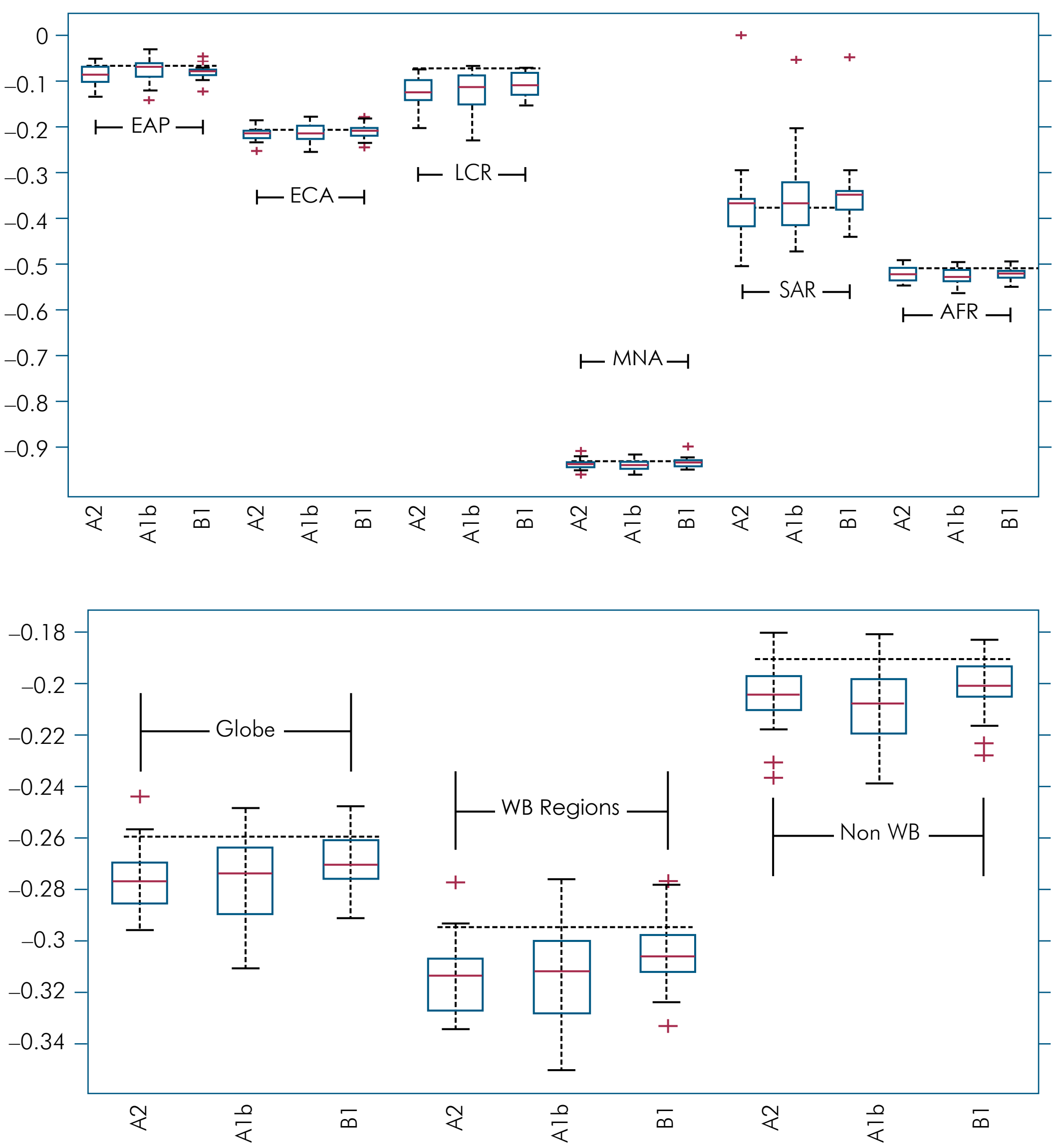
Projections of key hydrologic indicators for water planning

A common set of hydrologic indicators are projected for 2030 and 2050 for Bank regions. These are: runoff, basin yield, high and low flows (floods and droughts), minimum base flow (a proxy for shallow groundwater movement), and net irrigation demand. These indicators are projected at the catchment level, most appropriate scale for water planning and investment. The methodological approach used for this analysis was designed to capture the full spectrum of GCM climate projections. Twenty-two GCMs along with three emissions scenarios (B1, A1B, A2) are used to analyze changes in the key hydrologic variables in the years 2030 and 2050 from historical values in 1961–1990. In this analysis, GCM output is used as input to the hydrologic model CLIRUN-II (Strzepek, et al, 2008), developed specifically to assess the impact of climate change on runoff and to address extreme events at the annual level by modeling low and high flows. This analysis advances an earlier and much referenced effort by Milly, et al (2005). CLIRUN-II is stand-alone hydrologic model designed for application in water resource projects and generates output at a 0.5 x 0.5 degree grid scale, aggregated to approximately 2 x 2 degree resolution. The entire projection set reflecting the historical baseline conditions and projections for 2030 and 2050 is now available for all Bank regions.

In the context of downscaling, relying on results from a single or even just a few GCMs is not advisable. Care needs to be taken in selecting a method. Beyond reproducing the underlying uncertainties of GCMs, many introduce additional uncertainty and biases. This is because there

Climate Moisture Index: Range of CGMs for three emission scenarios for various regions

CMI Historic and Range of 2050 Climate Change Impacts

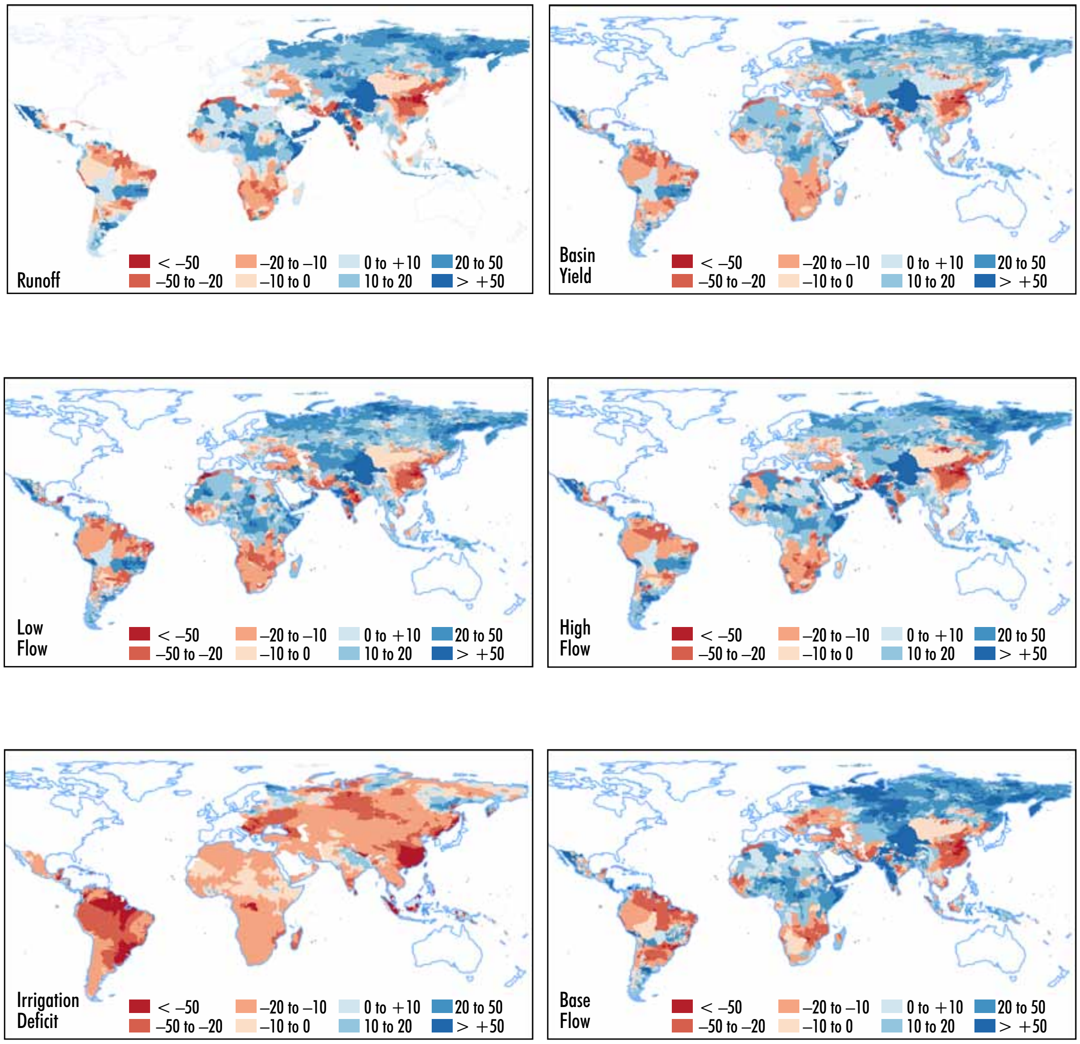


Legend

Top of box: 25th percentile
Bottom of box: 75th percentile
Whiskers: extreme CMI values

Red line: median CMI
Dashed line: historical CMI (1960–1990)
Cross hairs: model outliers

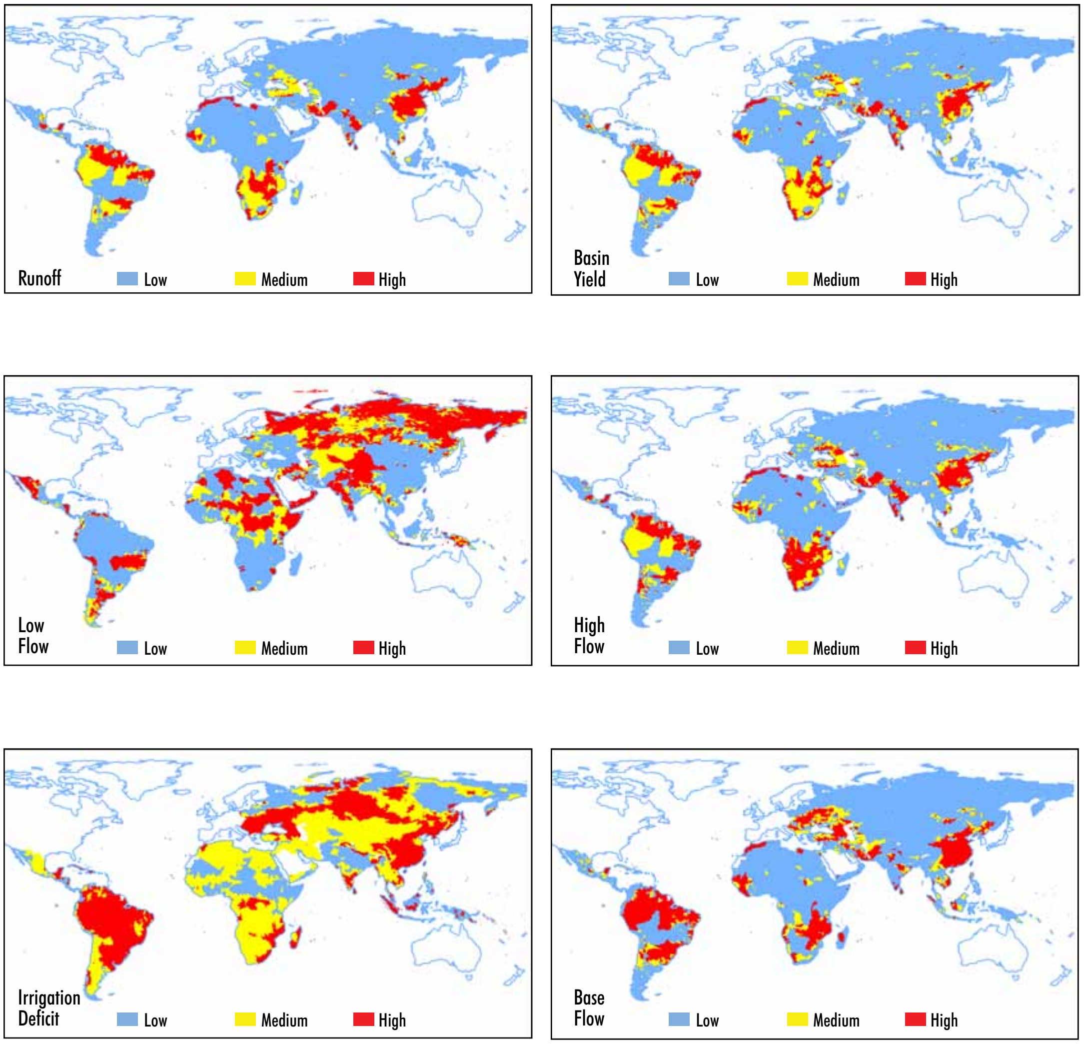
Projected percent change in hydrologic indicators for 2030 from 1961–1990 baseline



are model errors in any one model and natural variability (randomness) in any particular run. A single model, if run multiple times with differing initial conditions, can provide an estimate of the uncertainty due to natural variability. However, for any given model, there are also uncertainties associated with the assumptions made about model physics and parameterizations, as well as with the structural aspects of the model itself. Using a group of GCMs (multi-model ensembles), as opposed to one individual GCM, can account for biases and errors. The use of multi-model ensembles raises the question of how to capture the full range of results from model runs.

Climate Moisture Index characterizes the projected climate conditions. The calibrated historical model simulations and all of the 22 GCM projections for the three emissions scenarios for 2030 and 2050 are analyzed. The climate condition was categorized by the projected level of moisture (or aridity) using the Climate Moisture Index (CMI). The box and whiskers plots on the previous page show the climate moisture index projection for 2050 for Bank regions, as well as other regions. The height of the box indicates the degree of variability which results from the

Projected exposure map by hydrologic drivers (2030)



differences in means between different climate models. For example, in the LCR, 75% of the GCMs indicate drying with all 3 scenarios. The CMI for the SAR has the largest spread because of the way the different GCMs model the monsoons. In MNA, there is little variation because the area is so dry. Note that the land-based CMI projections for the Bank regions are more negative than non-Bank regions (e.g., OECD). However, the relative aridity (compared with the historical) for both Bank and non-Bank regions remains the same.

Projections at the catchment level allow for analysis of inter-regional variation at the project planning scale. Hydrologic indicators mapped for the Bank regions for the middle climate condition are shown in the figure on page xxiv. The general pattern is consistent with projections of runoff made directly from climate model runs. Here, specific indicators provide a deeper and more water-specific insight regarding potential changes in the water availability and distribution for various uses and by various water infrastructure interventions. For each region, detailed information for each of these indicators is available at the 0.5 x 0.5 degree resolution, as well as aggregated at the catchment level. It is planned that this information will be available via a web-based interface.

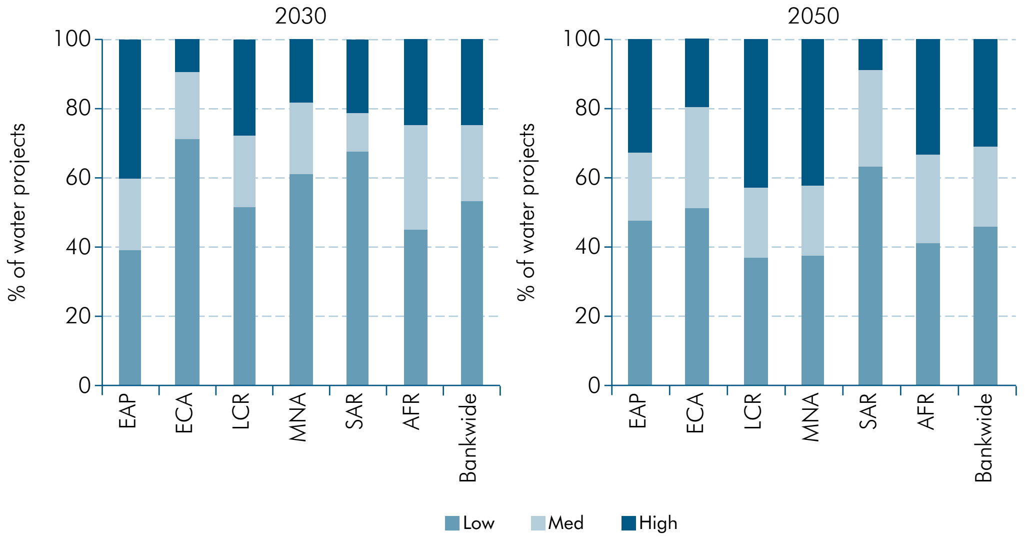
Exposure of the Bank investment to climate change

The World Bank's investments in the water sector are highly exposed, both to current variability and future climate change. The purpose of this assessment is to provide some sense of magnitude of the exposure of the projects and the financial investments they represent. Using threshold criteria for changes in each indicator, maps were created for high, medium, and low exposure categories for each indicator (see figure page xxv). Water projects, classified by water systems, are superimposed on the appropriate exposure map. The outcome is an exposure categorization of each water system according to its respective indicator. In this analysis, exposure to the impact of climate change for the following water systems on the Bank portfolio is assessed: irrigation and drainage, urban water supply and sanitation, rural water supply and sanitation, flood control, river basin management, and multi-purpose (supply water for multiple purposes). Results of the potential exposure of the active Bank water investments were they to operate in 2030 and 2050 are available.

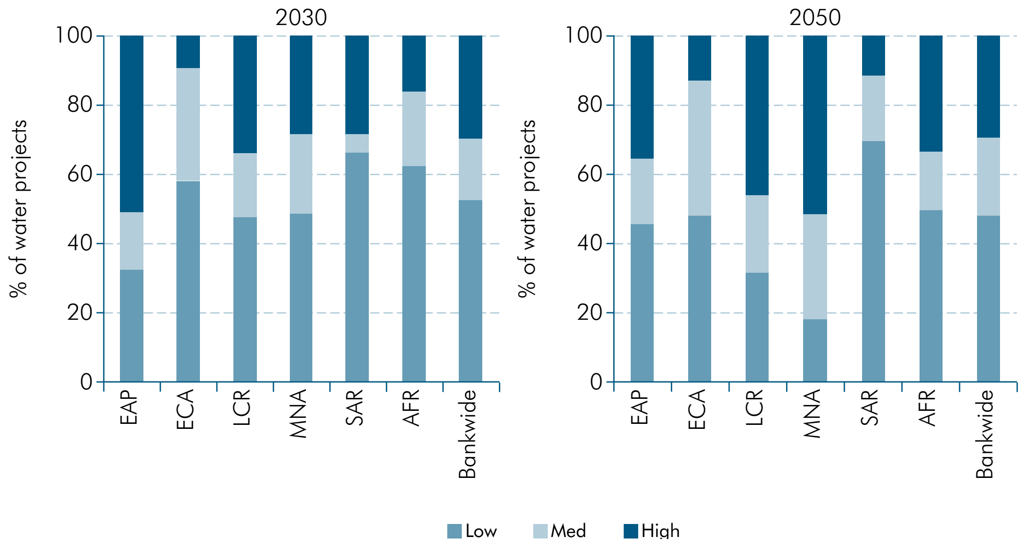
The following bar charts show the level of exposure of the Bank water investments to climate change by volume of investment and number of projects by region and Bank-wide. Similar charts, categorized by water systems, are available for each region and Bank-wide.

Projections indicate that about half of the Bank water projects reviewed would potentially be at high to medium level of exposure to climate change impacts in 2030. Within each regional portfolio, EAP shows close to two-third of projects with potential exposure to high/medium risk, possibly due to increased flooding. AFR and LCR show about half of the projects and MNA some 40% at potential high to medium risk of exposure. ECA and SAR show about one-third of the projects at potential risk of exposure to hydrologic changes. Projections for 2050 show exposure increasing for all regions except EAP. Obviously, the level of

Potential exposure of water projects to climate change in 2030 and 2050



Potential exposure of water investments to climate change in 2030 and 2050



uncertainty related to projecting climate change so far in time would be too high to make much of this difference.

In terms of investments, about half of the total water investments (including the pipeline) are projected at high/medium exposure level to climate change impacts in 2030. This translates to approximately $10 billion on the FY06–10 water projects reviewed here, risk associated with approval, delay, or drop of pipeline projects notwithstanding. The pattern of risk of exposure of investment roughly follows that of the projects. For 2050, climate change projections show an increase in MNA, AFR, LCR, and ECA, while expected to decrease in EAP, and SAR. Again, the uncertainty associated with the climate change projections in 2050 is considered quite high and therefore this conclusion should be viewed with caution.

Climate-smart investments must explicitly consider risk

Climate change projections contain a great deal of uncertainty and their use requires special care. The best available science is used here to assess the exposure of the Bank's water investments to the potential impact of hydrologic variability and climate change. None-the-less, substantial uncertainty remains regarding the real effects of climate change. There have been major advances in projecting the impacts—both from general circulation models and downscaling/statistical methods—which allows reporting general trends with some degree of confidence (including in temperature, precipitation, and extreme events). However, there are still significant unknowns, and even more challenging "unknown unknowns". There is no way around these uncertainties given the current state of the science—even agreement on a particular phenomenon across multiple models does not 'prove' that a given climate projection will indeed come to pass.

Reducing water sector's vulnerability to climate change means managing water under conditions of uncertainty. Water professionals have always dealt with and accounted for risk and uncertainty, but climate-change related uncertainties will require water to be managed fundamentally different than in the past. Historically, water planning was carried out under the key assumption of a stationary hydrologic pattern: the mean, variance and standard deviation of hydrologic time series fixed over time—commonly known as stationarity of hydrology. This assumption is no longer considered valid, forcing decision-makers to estimate hydrologic risks to water systems under even more uncertain conditions. The only viable approach in most investment cases is explicit consideration of risk and probability of occurrence of extreme events.

Water investments require a formal risk-based analysis in all aspects of the project/program cycle. Water systems are subject to both climate and non-climate related stresses, but there are certain types of water investments where uncertainties related to climate change could have a significant impact, and so particular care needs to be taken in undertaking a detailed, rigorous risk assessment. These include highly capitalized or unique projects, irreversible investments, engineering structures with long lifetimes, long-lived benefits and costs, etc. Examples include: multi-purpose hydraulic infrastructure, interbasin water transfer schemes, water conveyer systems for irrigated agriculture, regional/transboundary investments. Yet, there are water systems that are inherently resilient to some degree of hydrologic variability and climate change, are not significantly impacted, or the consequents of impact can be readily remedied. In these cases, a less rigorous risk assessment (screening level) may be sufficient.

Given the policy and financial implications of making water investment decisions, a more systematic approach is needed. Risk-based decision making is the systematic consideration of the probabilities, consequences, and values associated with different decision alternatives. In general, risk-based approach involves the following general stages: project objectives definition and characterization of the system components; knowledge of the likelihood and consequences of adverse events that could compromise those objectives; identification of the options for adapting the system or project to render it less vulnerable in the face of the identified risks; and assessment (either quantitatively or qualitatively) of adaptation options.

A special class of diagnostic indicators is used for the analysis of specific water resource systems or system design configurations and performance. Several measures of system performance have been proposed that permit the evaluation of a specific design configuration over a range of system inputs and service levels. Each indicator is based on the probability that a system, characterized by a given set of design parameters, will provide the intended level of services under a range of dynamic inputs and/or demand conditions. The measures of system performance are defined over a sequence of discrete time periods. Within each period, the system either performs (provides an acceptable level of services) or fails to do so. These indicators are: reliability; resiliency; vulnerability; and robustness.

Potential adaptation options can be categorized into those that carry 'no regrets' and those that are 'climate justified'. Many of the options to reduce vulnerability to climate variability are no different in a world with climate change than they are in a world without. These include demand management measures to increase water use efficiency and productivity, such as water-conserving irrigation technologies; wastewater recycling; economic incentives, including water pricing; and the encouragement of water markets that move water to high-valued uses. They also include, for example, measures to improve early warning systems and risk-spreading (e.g., disaster insurance). These options carry '*no regrets*' in that they would generate net social and/or economic benefits irrespective of whether or not anthropogenic climate change occurs. On the other hand, other actions might only be justifiable under man-made change in climatic variability. '*Climate justified*' measures may include, for example, constructing new infrastructure (dams, water conveyance systems, irrigation systems), retro-fitting existing infrastructure, changing rules of operation, tapping new sources of water (e.g., desalinization), water transfers, conjunctive use of surface and groundwater, innovative demand management, etc. However, many of these measures may be of the 'no-regrets' type depending on the specific circumstances. Whether they belong to one or the other category will have to be determined on a case by case basis.

The distinction between 'no regrets' and 'climate-justified' options is important in near-term and long-term decision making. For "no regrets" options, uncertainties in projections are to a large extent immaterial. By definition, these actions should be taken in order to meet current economic, social and environmental objectives, but they also serve the dual purpose of reducing vulnerabilities to future climatic conditions. It is in the realm of the 'climate-justified' that water managers will have to make difficult decisions about how to balance the political, economic, social and environmental costs of action versus of non-action, given an uncertain future. It is in this context that the indicators of performance listed above are used. The options selected should include plan and design for more resilient water interventions. The systems designed must be 'intelligent' and robust in the sense that they are able to deliver (near) optimal levels of service or management over a range of conditions, including through relatively modest re-design, retrofitting or re-operation. Implicit in robustness is also flexibility, that is, the ability to anticipate and react to a wider and largely unknown range of future climatic conditions.

There is a certain class of projects for which risk-based analysis would be particularly essential. Climate change will affect most water systems to some degree. However, some water services or resources by their very nature are more vulnerable to climate change than others. For example, small or distributed water supply systems that can easily make incremental changes at low cost are vulnerable to climate change, but may face less exposure to changes in climate, may be less sensitive to climate changes, or may have sufficient adaptive capacity to manage those changes. The systems listed below, however, are particularly vulnerable and special care should be taken to flag such water investments for risk-based analysis. These systems would likely be designed differently if climate change were taken into account, and failing to take climate change into account likely would cause significant economic loss (Hobbs, et al 1997).

- Highly capitalized or unique projects
- Engineering structures with long lifetimes
- Multi-purpose infrastructure systems
- Long-lived benefits and costs
- Systems susceptible to climate anomalies or extreme events
- Urban water supply

Way forward

Insight into the various dimensions of water and climate change has identified the gaps and guides the next steps. As the World Bank water agenda mainstreams adaptation to the impact of climate change, the questions raised in this report will continue to be an integral part of the ongoing work. These questions are: (i) what are the impacts of climate variability and change on water systems, both natural and engineered; (ii) what are adaptation strategies to reduce vulnerability of water systems to these impacts; and (iii) how can the Bank assist client countries in making informed decisions regarding adaptation options in their water investments?

In order to address these questions the following actions will guide the Bank's water practice: (i) continued strengthening of the analytical foundation, (ii) explicit incorporation of hydrologic variability and climate resiliency in project preparation and other bank operations (iii) a strengthening of Bank expertise on water and climate change.

In particular it is foreseen that: (i) the Water Anchor will up-date the projections of the hydrologic drivers for water investment presented in this report on a regular basis and make them more readily available for the regional staff for use through guidelines, notes, web-page etc. (ii) jointly with the regions there will be a further expansion and formalization of a risk-based approach to adaptation related investments (iii) guidelines will be provided for improved decision making by explicit incorporation of climate change effects in project economic analysis and through the preparation of assessments of the cost of adaptation and measures to reduce vulnerability at the river basin level.

Finally, in the future more work is needed on the impact of climate change on social and economic development.

CHAPTER 1:
CONTEXT AND OVERVIEW

Introduction

Evidence of increased hydrologic variability and climate change is solid. The Intergovernmental Panel on Climate Change has concluded that there is increasing evidence that the earth's climate is changing and at an unprecedented rate (IPCC, 2007a)[1]. This is contributing to increased frequency and magnitudes of extreme events, including both floods and droughts (e.g., 2007–8 floods in South and East Asia, 2006–7 droughts in parts of Africa and Middle East, 200–009 drought in Australia). Accelerated glacial melt has been documented in the Andes in South America, the Himalayas in Asia, and even on Mt. Kilimanjaro in east Africa. Sea level rise is already threatening many major coastal cities and small islands.

Warming of the climate system in recent decades is 'unequivocal' (IPCC, 2007a). The earth's temperature is highly variable, with year to year changes often masking the overall rise of approximately 0.74°C that has occurred from 1906–2005. Nevertheless, there is a clear twentieth century upward trend, and in particular a rapid rise over the past 50 years. Indeed, the period from the 1980s onwards has been the warmest period in the last 2000 years. The IPCC has projected that by the end of the 21st century, the earth's average temperature is likely to rise by between 1.1 and 6.4°C from the mean in 1990, depending on the emission path.

And human activities are in part responsible. Greenhouse gases that trap heat (water vapor, carbon dioxide, and methane) exist naturally in the atmosphere. However, there is increasingly strong evidence that 'anthropogenic forcings'—and in particular increasing concentrations of CO_2 from the burning of fossil fuels—have contributed to global warming. According to the IPCC, most of the observed increase in global temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations (IPCC, 2007a). This also holds at the continental scale for all regions except Antarctica.

Responses to climate change take two linked tracks—mitigation and adaptation. Mitigation seeks to minimize the human footprint through efforts to control, reduce or even eliminate greenhouse gas emissions. This is generally referred to as a transition to low or constrained carbon growth. Examples include the introduction of low-carbon technologies for electricity generation and transport, reforestation, and capturing and sequestering emissions. Because the effects of historical greenhouse gas emissions cannot be reversed, attention is increasingly being given to the need for adapting to a changing climate. Adaptation attempts to reduce the vulnerability of human livelihoods, economies, and natural systems to the impact of climate induced changes. Examples include (a) increasing the resiliency of the agricultural sector to droughts and reducing the risk of floods through improved storage and infrastructure management and (b) protecting freshwater ecosystem functions by integrating environmental flow requirements in infrastructure planning, design and operations. In some cases (e.g., hydropower, wetlands management) mitigation and adaptation strategies may be closely linked and complimentary.

This report contributes to the World Bank agenda on climate change and more specifically, informs the water sector investments on climate issues, risks and climate-

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[1] All references to IPCC literature comply with the specific citation format indicated by IPCC.

smart adaptation options. Using the existing knowledge and additional analysis commissioned by the World Bank, the report intends to illustrate that climate change is affecting the hydrologic cycle and projections show direct impact on the water resources base. Depending on the water investment, this impact can be positive, negative, or neutral. The report distinguishes between stress on and vulnerability of the water systems through use of reliability, resilience, and robustness as the key indicators of performance. Current practices in the sector are examined in order to better understand the state-of-the-science for incorporating current and future variability and change in hydrology and climate in the Bank's portfolio. New and innovative practices taking into account adaptation options for water systems and risk-based decision making in water investments are reviewed and assessed for application to major Bank investments in infrastructure. The climate change dimension is placed within the context of the impact of other factors (within and outside the sector) such as population growth (and associated increase in demand) and land management, which may be far more significant and critical than that of climate change in some cases and in some parts of the world.

Climate Change and the World Bank

Climate change is a development issue for the Bank and its clients. WBG clients, by virtue of their geographic location and often low coping capacity, are among the most affected. The Bank's 2007 report *IDA and Climate Change: Making Climate Action Work for Development* provides compelling evidence that the distribution of major climate-related risks around the world is skewed against poor countries. The Bank's 2009 Development and Climate Change Strategic Framework (DCCSF) (World Bank, 2008a) asserts that climate change is a development issue, among others. DCCSF states: The anticipated impacts of climate change, which could begin to occur within the next two to three decades, include: dangerous floods and storms and more frequent and longer droughts; exacerbated water stress; decline in agricultural productivity and food security; increased saltwater intrusion in coastal aquifers and estuaries; increased stress on freshwater ecosystems; and further spread of water-related diseases, particularly in tropical areas. This could lead to population displacement, migration, and potential conflicts. In the longer term, sea level rise and glacier melting threaten the existence of nations and the development foundation of subcontinents.

Sub-Saharan African countries dominate the list of most climate-affected client countries. Other regions are also affected by extreme events (e.g., South and Southeast Asia flooding, Latin America and South Asia rapid glacial melt). Climate change poses a risk to World Bank investments in a wide range of sectors, including potentially undermining performance, sustainability and contributing to water scarcity and water security in certain cases. This makes it imperative that climate change adaptation is not separated from other priorities, but, rather, is integrated into development planning, programs and projects in the client countries.

Climate change has direct implications for the World Bank's mission of poverty reduction. The Bank's 2009 Development and Climate Change Strategic Framework (DCCSF) states: "climate change threatens to reverse hard-earned development gains. The poorest countries and communities will suffer the earliest and the most. Yet they depend on actions by other nations. While climate change is an added cost and risk to development, a well-designed and well-implemented global climate policy can also open new economic opportunities to developing countries." Indeed, developing countries, and particularly the poorest people in these countries, are the most vulnerable to the adverse impacts of climate variability and projected climate change. Their economies depend heavily on climate-sensitive sectors such as agriculture, livestock, forestry, fisheries, water supply, and other natural resources. They are generally hindered by limited institutional capacity and access to technology and capital to invest in risk reduction. World Bank analysis of Ethiopia, Mozambique and Kenya shows huge impacts of climate variability on the performance of key economic sectors such as agriculture, transport, energy, manufacturing, livestock and tourism. Estimates of the economic impacts of climate change are likely to be significant, especially in developing countries (Stern, 2006). However, these can be minimized and reduced with appropriate adaptation strategies.

Addressing climate variability through both mitigation and adaptation has been, and continues to be a key priority for the Bank. For decades, the World Bank has been actively engaged in efforts to mitigate climate variability. The World Bank has provided countries with incentives to develop and implement clean energy technologies and sustainable transport systems, as well as to improve practices in agriculture, forestry and land management. This has allowed many countries to achieve increased energy access for the poor and improved livelihoods for the vulnerable, while at the same time moving towards a sustainable, low-carbon path of development. More recently the focus has also turned to adaptation. DCCSF articulates the WBG's vision on how to integrate climate change and development challenges, without compromising growth and poverty reduction efforts through its country operations, including policy dialogue, lending, and analytical work in client countries, and through its regional and global operations. A coordinated way to finance the mitigation and adaptation efforts is through the Climate Investment Funds (CIFs). These funds are established to serve as interim financing to developing countries in addressing climate change issues. The WBG is among the Multilateral Development Banks (MDBs) that will engage in partnership with developing countries in their transition to a carbon-constrained and climate resilient economies.

Climate change and the water sector

The World Bank is responding by first understanding the risks and impacts, then managing them through climate-smart investments. The World Bank recognizes water as a key affected sector. Consequently, the impact of climate change and potential adaptation strategies has become central to the dialogue on water policy reforms and investment programs with client countries. This has been guided by climate change strategies prepared by each region of the World Bank within the context of the DCCSF. The 2010 World Development Report focuses, among other factors, on the land and water interface for managing competing demands and creating new opportunities for climate-smart development. Many client countries in partnership with the World Bank Group have begun to take action to adapt their water sector to implications of climate change and resulting hydrologic impacts. This process is supported by analytical and advisory assistance on water and climate change carried out by Regional Units, as well as the Water Anchor. Incorporating climate change in the portfolio has been steadily increasing in response to client demands. A number of stand-alone climate change projects have also been financed through various grant and lending instruments and they are increasing.

There is strong link between changes in climate and the hydrologic cycle. According to the IPCC's most recent report, "*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 on human societies and ecosystems* (Bates, et al, 2008, p.4). Long-term trends in hydrologic variables are difficult to detect due to significant natural variability in all components of the hydrologic cycle over both time and space.[2] However, ***observed*** changes in the hydrologic cycle at the sub-continental scale have consistently been associated with climate warming over the past several decades. These changes are often referred to as intensification and acceleration of the hydrologic cycle. These changes include increasing atmospheric water vapor content; changing precipitation patterns, intensity and extreme events; reduced snow cover and faster and widespread melting of ice; and changes in soil moisture and runoff. It is ***projected*** that many of these phenomena will become more pronounced with climate change.

Climate change could profoundly alter future patterns of both water availability and use, thereby increasing water stress globally. Many of the direct effects of climate change on water availability have been presented above. However, less is known about the impacts of climate change on groundwater availability and use, including interactions with surface water. There is also relatively little information on freshwater ecosystems and water quality, although according to IPCC (and other studies) higher water temperatures and changes in extreme events, including floods and droughts, are projected to affect water quality and exacerbate many forms of water pollution. In addition, sea-level rise is projected to extend zones of salinisation of groundwater and estuaries. Taken together, the potential changes in water availability and use may aggravate global 'water stress'. Most studies have found that levels of water stress will increase, although there are significant differences in estimates across studies. Arnell (2004)—who accounts for population growth and the impact of climate change—found that the number of people projected to experience an increase in water stress is between 0.4 to 1.7 billion in the 2020s and between 1 and 2.7 billion in the 2050s (using the A2 population scenario for the 2050s). When environmental flow needs are incorporated—that is, the amount of water required to sustain a functioning ecosystem—the degree of water stress is projected by some to increase further (Smakhtin et al, 2003).[3] Based on these and other studies, *the IPCC concluded with high confidence that, globally, the negative impacts of future climate change on freshwater systems and ecosystems are expected to outweigh the benefits.*

Future water availability, use, and investments will also depend on non-climatic drivers, including financial and sector conditions. Climate change is only one of many factors that will determine future patterns of water availability and use. Non-climatic factors could aggravate or attenuate the adverse effects of climate change on water availability and quality, as well as have a significant influence on water demand. Population growth and economic development (and, by extension, changes in lifestyles and diets) will play a dominant role. Non-climatic impacts could be generated through many realms—from policies and legislation to technologies and infrastructure to land-use patterns and agricultural activities/irrigation. Additionally, water infrastructure investments are highly sensitive to the trends of the Official Development Assistant (ODA), availability of financing through Multilateral Development Banks (MDB), and the private sector appetite for investment. Recent financial crisis and sector crises (e.g., food, energy) have already shown their impact on the water sector and will continue to remain a major challenge. Such non-climatic drivers could dwarf the impacts attributed to climate change alone, in a positive or negative direction. The impact of the financial crisis on water infrastructure *vis a vis* deferred operation and maintenance can be particularly devastating.

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[2] Large-scale atmospheric circulation patterns associated with ENSO (El Niño-Southern Oscillation), NAO (North Atlantic Oscillation) and other variability systems that operate at within-decadal and multi-decadal time-scales are a very strong influence in some regions.

[3] Note that such indices of water stress are typically defined in terms of annual averages and do not include varying levels of water quality.

Water investments are particularly vulnerable to impacts of climate change. Climatic impacts will have significant consequences on investments in water systems[4] (or infrastructure) associated both with delivering water services and with managing water. Water systems for delivering water services include irrigation; urban water, sanitation and drainage; rural water and sanitation; and ports and navigation. Systems for managing water resources include those for delivery of bulk irrigation, watersheds, and water resources broadly, as well as multi-purpose systems (including hydropower) and flood control. For example, in urban environments, more heavy rainfall events could overload the capacity of storm drain systems and water and wastewater treatment facilities; sea level rise could lead to salinisation of water supplies from coastal aquifers. Climate change could increase irrigation demand due to the combination of decreased rainfall and increased evapotranspiration, placing additional pressure on irrigation systems that are in many cases already under performing. Changes in river flows have a direct impact on hydropower generation. Soil erosion from increased rainfall intensity could affect watershed sustainability and lead to sedimentation in reservoirs, impacting on the operation of multi-purpose facilities. Extreme variability and/or reduced supplies could stretch the infrastructural and institutional limits of systems that manage water across sectors and even national boundaries.

The extent to which water investments are impacted by climate change will have ramifications that could extend to the economy and society at large. This depends highly on the degree of vulnerability of the system (or project) design and operation, including its internal capacity to adapt. For example, pressure on water supply and sanitation facilities could have a wide range of adverse effects on human health. Reduced availability of water for irrigation could threaten food security, rural development, environmental uses of water, and the economies of countries that are largely dependent on the agricultural sector. Reduced freshwater supplies may lead to a shift towards increased use and dependence on groundwater. Reduced water for hydropower generation (or increased fluctuations in river flows) could decrease electricity grid stability and reliability, with consequent effects on the economy as well as livelihoods dependent on downstream uses of water. Managing sedimentation (e.g., through flushing) could affect the timing, supply and quality of water to the various sectors served by a multi-purpose infrastructures, with impacts felt in the larger economy. In the worst case, competition over limited water resources across sectors and nations could worsen hostility and mistrust, and increase conflicts over water and further degrade freshwater ecosystems.

Value added and content of this report

The primary objective of this report is to support Bank operations and the client countries in making informed and climate-smart water investment decisions. This report provides an overview of a package of background technical reports, papers, and analyses commissioned by the Bank's Water Anchor in an attempt to understand the risks of the impact of climate change on the Bank's water investments and to provide ways to manage them. This package of information, knowledge, and guidelines is intended for use by the Bank water staff and client countries.

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[4] The term 'system' in captures all elements—from infrastructure to institutions—that contribute to performance of the intended function. In this report, system and infrastructure is sometimes used interchangeably with water systems with the implied broadest definition of the term.

This report adds value to the Bank's work on climate change and water in the following areas:

A compilation of the state-of-the-knowledge for the Bank's water practice. There is a wealth of information on climate change, adaptation and the water sector, which is held within the Bank and beyond, and which includes both analytical studies and on-the-ground experiences. The body of knowledge on this subject is rapidly expanding. A significant added value of this report is in bringing together the various information, references, and conclusions from this vast knowledge base in a condensed, structured and coherent manner specifically useful to the Bank's water practice. Another value of this report, equally important to the water professionals is provision of the best available information regarding the gaps in the knowledge, critical assumptions made in the modeling effort, shortcomings and pitfalls in the analysis, and potential misuse of the results.

A consolidated package of historical data and projections of key hydrologic drivers useful for policy, planning, and investment decisions in the sector. One potential difficulty with using climate information in impact assessments—including in the water sector—is the 'mis-match' between the low spatial (and temporal) resolution of GCMs, on the one hand, and the scale at which assessments need typically to be conducted for investment purposes, on the other. To facilitate initial dialogue and assessment for incorporation of climate change in water investments, a set of historical and projected hydrologic parameters have been compiled for Bank use. The historical information is based on 1960–1990 period organized to serve as baseline. The projections are based on projections from 22 GCMs, scaled to basin level and translated to hydrologic drivers and indicators for planning and investment decisions.

An analysis of the exposure of Bank water investments to current hydrologic variability and future climate change. The World Bank's water investments are exposed to current hydrologic variability and future climate change. The historical and future hydrologic drivers and indicators are mapped on to the Bank's active and pipeline projects to assess the potential exposure to hydrologic variability and climate change. Assessment of the exposure of the water services investments (e.g., irrigation and drainage, urban water supply and sanitation, rural water supply and sanitation) and water management systems (e.g., flood control, river basin management, and multi-purpose infrastructure) are reported here.

Climate change implications on groundwater and groundwater management adaptation opportunities are highlighted. Relative to surface water, aquifers have the capacity to store large volumes of water and are naturally buffered against seasonal changes in temperature and rainfall. They provide a significant opportunity (through conjunctive use and management of surface and groundwater resources, managed aquifer recharge and land use protection and management) to optimize use of water resources, to store excess water during high rainfall periods, to reduce evaporative losses and to protect water quality. However, these opportunities have received little attention, in part because groundwater is often poorly understood and managed.

Freshwater ecosystem adaptation options. As hydrology and water use changes due to altered precipitation patterns and as waters become warmer, freshwater ecosystems will be stressed further and the aquatic life they now support will be replaced by other species better adapted to warmer water (i.e., cold water fish will be replaced with warm water fish). This process, however, will occur at an uneven pace disrupting ecosystem health and allowing non indigenous and/or invasive species to become established. In the long term, warmer water and changing river flows may result in significant deterioration of aquatic ecosystem health in some areas (USEPA, 2008). A key response to climate adaptation is to develop both adaptive management systems that can enable ecosystems to respond to changes and the establishment of resilient ecosystems.

Guidance on inclusion of risk-based decision making in water investments. World Bank water investments can have significant exposure and vulnerability to climate change. Most water investments can no longer be designed based on average conditions and simplified, deterministic assumptions. To avoid or reduce climate-induced losses, a shift in decision making from traditional deterministic approach to a risk-based approach is necessary. This will help to better understand (and characterize) the risks and develop ways to manage them. A framework for systematic and pragmatic incorporation of risk and uncertainty in the Bank's water investment project cycle is presented in this report.

The content of this report will help enhance sustainability of Bank investments in the water sector by providing staff and client countries. The report presents/summarizes approaches, methodologies and guidelines for incorporating hydrologic variability, climate change, and risk management in project, program and sector-wide investments. It will contribute to preparation of future country water resources assistance strategies that incorporate adaptation to climate change in investment planning and inform institutional and policy reform for sustainable management of water resources. The report begins with illustrating the impact of climate change on the hydrologic cycles and identifies the drivers significant to investments. The scientific effort to understand and describe climate change is assessed for application to the Bank operations. The impact of the changing hydrologic cycle on water availability, demand, and management, including the potential vulnerability of various water systems and its implication in the sector is then examined. A package of climate change projections at a scale appropriate for planning and investment decisions had been developed. This package is designed to serve as a common basis for analysis of the impact of climate change in any sector. Using these projections, exposure of the current and future Bank portfolio to climate change is evaluated. Finally, an agenda for continued effort in the water practice to address hydrologic variability and climate change is proposed.

The primary audience for this report and its associated technical reports is World Bank staff and as appropriate the client countries. The objective is to equip Bank staff with needed knowledge and tools to effectively incorporate climate variability and change in their operational work in the water sector. The outcome of this work will also assist client countries in making informed decisions on incorporating hydrologic variability and adaptation strategies into long-term planning and investment decisions. This is timely and relevant as both the Bank staff and client country professionals are becoming increasingly aware of the risks of no action. A comprehensive dissemination strategy, including capacity building programs, for Bank staff and clients countries will be developed by the Water Anchor and implemented in collaboration with the regions and as part of the World Bank Institute climate change activities.

CHAPTER 2:
IMPACT OF CLIMATE CHANGE ON THE HYDROLOGIC CYCLE AND THE WATER RESOURCE BASE

The climate system and the hydrologic cycle are intimately linked

Powered by solar radiation, the climate system is a complex, inter-active system consisting of the atmosphere, land surface, snow and ice, oceans and other bodies of water, and living things (IPCC, 2007a). The climate system evolves over time under the influence of its own internal dynamics and due to changes in external factors that affect climate (called 'forcings'). External forcings include natural phenomena (e.g., volcanic eruptions and solar variations), as well as anthropogenic changes that alter atmospheric composition and land-use change. Changes in any of these factors can alter the balance between incoming (solar) short-wave radiation and outgoing long-wave radiation. The climate system responds both directly and indirectly (through feedback mechanisms) to such changes. Description of weather, climate, and climate variability are provided in Box 2.1.

Any variability in climate affects the hydrologic cycle.[5] The hydrologic cycle describes the continuous movement of water through the oceans, atmosphere, and land surface (Figure 2.1). Driven by solar energy, the hydrologic cycle begins with the evaporation of water from the surface of the ocean. As moist air is lifted, it cools and water vapor condenses to form clouds. Moisture is transported around the globe and returns to the surface as precipitation (in its multiple forms of rain and snow, sleet, hail, etc.). Once the water reaches the ground, one of two processes may occur: i) water evaporates or transpires back into the atmosphere[6] or ii) the remaining water penetrates the surface and becomes groundwater. Groundwater seeps into oceans, rivers, and streams. The balance of water that remains on the earth's surface is runoff, which empties into lakes, rivers and streams and is carried back to the oceans, where the cycle begins again (Bramer et al., 2008).

Box 2.1 Weather, climate, and climate variability

Weather is a measure of short-term changes in atmospheric conditions (e.g., temperature, precipitation amount, humidity). ***Climate*** describes the typical weather of a region. More precisely, it is a statistical description of long-term (e.g., 30 years) average, variances, and extremes derived from observed weather. ***Climate variability*** generally refers to fluctuations around a mean climate that occur on seasonal, inter-annual, and even decadal timescales. A significant component of climate variability can be linked to a relatively small number of patterns (or modes) of variability, including El Niño-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Atlantic Multi-decadal Oscillation (AMO). These events—which may occur on timescales of years to decades—lead to changes in atmospheric circulation and rainfall distribution that characterize many parts of the world. A key point is that these patterns are not long-term changes in climate, but rather deviations from mean climate conditions.

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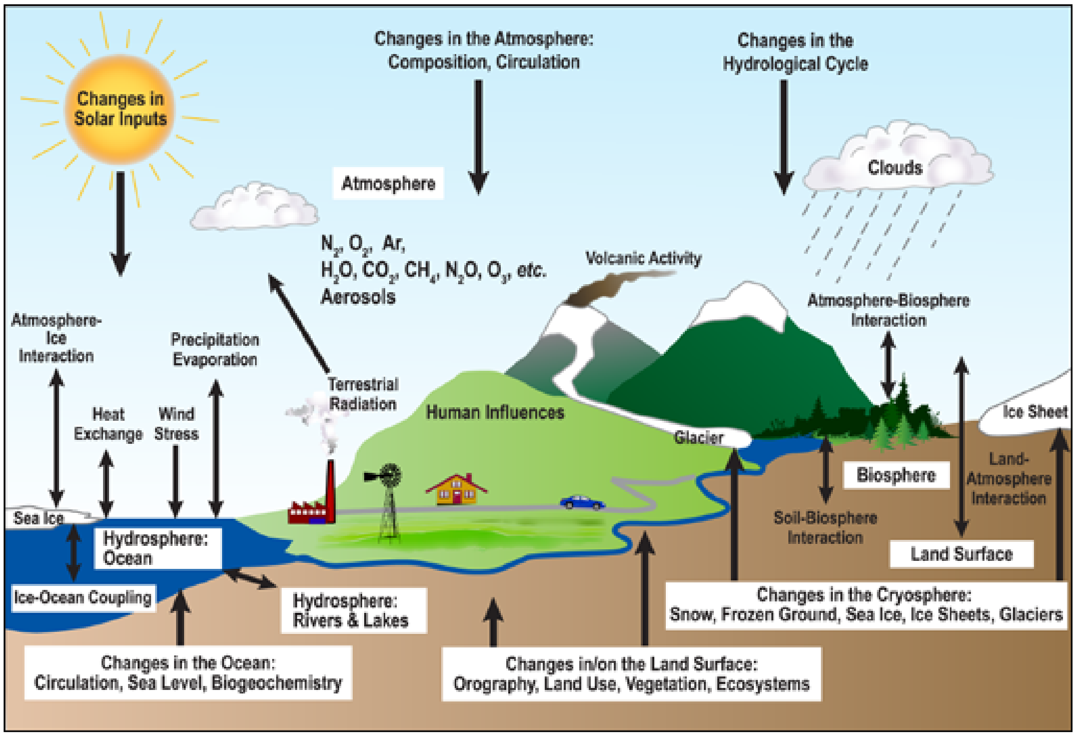
[5] The influence also works in the reverse direction, i.e., the changes in the hydrologic cycle can also affect the climate system. The focus here, however, is on the impact of climatic change on hydrology.

[6] Evaporation is water that turns to water vapor directly from surface water bodies (e.g., oceans, lakes, and reservoirs). Transpiration is water that is taken up by plants and then released to the atmosphere.

Figure 2.1 The Hydrologic Cycle



Source: IPCC 2007c, pg. 96, FAQ1.2, Fig. 1.

Evidence is mounting that climate change is occurring and that it is altering the hydrologic cycle

Climate change is "an altered state of the climate that can be identified by changes in the mean and/or variability of its properties, and that persists for an extended period, typically decades or longer" (Bates, et al., 2008). Definitions of climate change vary, not in terms of what it is, but in terms of what is responsible, and specifically whether it is attributable to natural causes and/or anthropogenic causes. The United Nations Framework Convention on Climate Change (UNFCCC) definition of climate change is restrictive, in the sense that it includes only anthropogenic-induced changes and not those associated with natural causes. The Intergovernmental Panel on Climate Change (IPCC) definition, which includes both, is more widely accepted, so it is adopted here. According to the IPCC definition, climate change can be attributed to natural internal processes and to external forcings, both natural and anthropogenic.

While there is wide agreement on the potential causes of climate change, it is difficult to attribute observed (or detected) changes in climate to a specific cause, and, in particular to anthropogenic changes. The difficulties of distinguishing between human and natural causes of climate change increase at finer spatial and temporal scales. Nonetheless, the IPCC has found, based on a number of observed trends, that global climate is changing, and that it is *very likely* that human activities are in part responsible. The earth's temperature is highly variable, with year to year changes often masking the overall rise of approximately 0.74°C that has occurred from 1906–2005 (IPCC, 2007a; Bates, et al., 2008). Nevertheless, there is a clear twentieth century upward trend, and in particular a rapid rise over the past 50 years. Greenhouse gases that trap heat (water vapor, carbon dioxide, and methane) exist naturally in the atmosphere. However, there is increasingly strong evidence that anthropogenic radiative forcings—and in particular those deriving from increased concentrations of CO_2 from burning of fossil fuels—have contributed to global warming.

There is now strong evidence that global warming is changing hydrologic cycle. Long-term trends in hydrologic variables are difficult to detect due to significant natural variability in all components of the hydrologic cycle over both time and space. However, observed changes in the hydrologic cycle at the sub-continental scale have consistently been associated with climate warming over the past several decades.[7] A summary of the evidence, based on IPCC findings is provided below (Bates, et al., 2008; Kundzewicz, et al., 2007).

Precipitation (including extreme events) and water vapor:

- The average atmospheric ***water vapor*** content has increased since at least the 1980s over land and ocean as well as in the upper troposphere.
- Over the 20th century***, mean precipitation*** has mostly increased over land in high northern latitudes over the period 1901 to 2005, while decreases have dominated from 10°S to 30°N since the 1970s.
- Widespread increases in ***heavy precipitation events*** (e.g., above the 95th percentile) have been observed, particularly in mid-latitude regions and even where total precipitation has decreased.
- Globally, ***soil moisture*** has decreased. ***Droughts*** have become more intense and longer, especially in the tropics and subtropics.
- There is observational evidence that intense ***tropical cyclone*** activity has increased is some regions (e.g., North Atlantic since about 1970). There is no clear trend in the frequency of tropical cyclones.

Snow and land ice:

- ***Snow cover*** has decreased in most regions, especially in spring and summer; degradation of ***permafrost and seasonally frozen ground*** has occurred in many areas; freeze-up and break-up dates for ***river and lake ice*** have been delayed and taken place earlier, respectively, in the Northern hemisphere, where data are available.
- Considerable mass loss has occurred on the majority of ***glaciers and ice caps*** worldwide (Box 2.2).

Future changes in climate are projected to lead to a further acceleration and intensification of the hydrologic cycle

Changes in the global climate system during the 21st century will *very likely* be larger than those observed during the 20th century. The IPCC has projected that by the end of the 21st century, the Earth's average annual mean temperature is *likely* to rise by between 1.1 and 6.4°C from the mean in 1990. The wide range in projections of mean surface air warming result from two factors: The SRES (Special Report on Emissions Scenarios) emissions scenario and different models used. However, the IPCC concluded that it is *very likely* that nearly all land areas will warm more rapidly than the global average and particularly those at northern high latitudes in the cold

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[7] There are several processes through which changes in hydrological variables can produce feedback effects on climate (e.g., land surface effects, feedbacks through changes in ocean circulation, emissions or sinks affected by hydrological processes), but the focus here is in the reverse direction, that is, the impact of climate change on hydrology.

Box 2.2 Mass loss of glaciers

Tropical glaciers located between Bolivia and Venezuela decreased in area by just under 20% between1970 and 2002. Several glaciers in South America, such as Ecuador's Cotacachi, have already disappeared (EOS, 19 June 2007). Peruvian glaciers declined nearly 22 percent between 1970 and 1997 as a result of warmer temperatures. Major additional reductions in surface area have been measures since then. The largest of these glaciers in the Cordillera Blanca have lost 15 percent of their glacier surface area in a period of 30 years. Many of the smaller glaciers in Peru have already been heavily affected and others are likely to completely disappear within a generation.

Evidence suggests that the rate of temperature increase in Nepal and the Tibetan Plateau is greater than the global average, and a pronounced warming in winter has already been observed. Retreating glaciers in the Himalayas present one of the most difficult challenges for the region, because glaciers and snow provide water storage that helps to regulate the flow of perennial rivers and to enhance low season flows. The Himalayan glaciers are reducing at a rate of 10–15 m every year (Tehelka, 3 May 2008). The region is also at risk of an increase in the frequency and magnitude of climate change-related natural disasters, including glacier and snow melt, and glacial lake outburst floods.

Observed and anticipated climate change-related impacts include deterioration of watersheds and depletion of water recharge capacities, increased likelihood of mountain fires, and biotic changes in ecosystem thresholds and their ability to store water. The effects and consequences may be different at the initial and final stages of the glacier retreat and may differ depending on location.

season. Climate variability is also *likely* to change, although the nature of this change is uncertain. Along with the substantial changes in average climatic conditions, it is *likely* that there will also be changes in the seasonal cycle of the climate and in the intensity and frequency of extreme events (refer below).

It is projected that many of the currently observed changes in the hydrologic cycle will become more pronounced with continuing climate change. Projected increases in global temperatures are associated with changes in the hydrologic cycle, including increasing atmospheric water vapor, changes in precipitation patterns (frequency and intensity), leading to changes in soil moisture. These changes are often referred to as an *intensification and acceleration of the hydrologic cycle*. The result of hydrologic change and increased variability is shorter periods of more intense rainfall, and longer warmer dryer periods. IPCC findings on the projected impacts of climate change on the hydrologic cycle are summarized below (Bates, et al., 2008; Kundzewicz, et al., 2007).

- ***Annual average precipitation***: Precipitation is projected to increase in high latitudes (very likely) and parts of the tropics, and decrease in some subtropical and lower mid-latitude regions (likely).
- ***Precipitation Extremes***: Increased precipitation intensity and variability is projected to increase the risk of flooding and drought in many areas (increased rain-generated floods very likely, increased extreme drought likely). It is likely that future tropical cyclones will become more intense, with larger peak wind speeds and heavier precipitation.
- ***Glaciers and snow***: Water stored in glaciers and snow cover is projected to decline (high confidence).
- ***Sea level***: In all but one SRES marker scenario (B1), the average level of sea level rise during the 21st century will very likely exceed the 1961–2003 average rates. Thermal expansion is the

largest component. It has been suggested that melting of glaciers, ice caps and the Greenland Ice Sheet can contribute to sea level rise as a result of shift in the gravitational pull created by significant loss of mass at the poles.

- ***Evapotranspiration***: Changes in temperature, radiation, atmospheric humidity and wind speed affect potential evapotranspiration (or evaporative demand). In addition, increasing atmospheric CO_2 concentration directly alters plant physiology, thus affecting evapotranspiration. Potential evaporation is projected to increase almost everywhere. Transpiration may increase or decrease.
- ***Soil moisture***: Annual mean soil moisture content is projected to decrease in the sub-tropics and the Mediterranean region, and at high latitudes where snow cover diminishes. Soil moisture is projected to increase in East Africa, central Asia and other regions with increased precipitation.

Table 2.1 summarizes the observed trends and projections for the 21st century of key hydrologic variables.

Table 2.1 Changes in Key Hydrologic Variable

Key Variables	***Observed Trends***	***Projections for 21st Century***
Total Precipitation	Trend is unclear. General increases in precipitation over land from 30°N to 85°N. Notable decreases from 10°S to 30°N.	Increase (about 2%/°C) in total precipitation. High latitude areas generally projected to increase. Many low to mid-latitude areas projected to decrease. Changes at the regional scale vary.
Atmospheric Water Vapor Content	Increasing in lower atmosphere (lower troposphere; about 1%/decade) in specific humidity; little change in relative humidity	Increasing
Intensity of Precipitation	Disproportionate increase in volume of precipitation in heavy or extreme precipitation events	Increasing (about 7%/°C)
Droughts	Drought, as measured by the Palmer Drought Severity Index, increased in the 20th Century, although some areas became wetter	Increasing in many areas, particularly lower latitudes. Decreasing in many high latitude areas. Patterns are complex.
Tropical Cyclones	Increases in intensity, particularly in North Pacific, Indian Ocean, and Southwest Pacific	Increase in intensity. Changes in frequency and track are uncertain
Glaciers and snow cover	Decrease in mass of glaciers, but not in all regions. Decrease in snow cover in regions in the northern Hemisphere. Earlier peak runoff from glacier and snowmelt.	Continued decrease in glacial mass and snow cover
Sea level	Increased about 0.2 meters over the 20th century. A rise equivalent to 0.3 meters per century was recorded since the early 1990s, but it is not clear if this is an acceleration of long term sea level rise	IPCC projects 0.2 to 0.6 meters by 2100, but upper end could be much higher.

Source: Derived from IPCC, 2007a; Kevin Trenberth, National Center for Atmospheric Research. Personal Communication. May 19, 2008; Trenberth et al., 2003.

Hydrologic change and increased variability will have a significant impact on the water resource base

Changes in the hydrologic cycle will have both direct and indirect effects on the magnitude and timing of runoff, groundwater recharge, water quality, and the frequency and intensity of extreme events (droughts and floods). Projected impacts on each on these components of the water resource base—summarized from various IPCC reports—are provided below.

Uncertainties in projected climate change impacts

There are significant uncertainties in projections of the impact of climate change on the water resource base. These uncertainties derive from a number of sources, including from internal variability of the climate system, uncertainty in future emissions, the translation of these emissions into climate change by global climate models, and model uncertainty (Bates, et al., 2008). Uncertainties in projections increase with the length of the time horizon, and temperature is projected with more certainty than precipitation. Where hydrological models are used to project changes on water resources, uncertainties arise from the mismatch between their respective spatial and temporal scales. Downscaling methods have been used to address the scale issues, but they introduce additional uncertainties. The greatest uncertainties in the effects of climate on river discharge/runoff arise from climate change scenarios, as long as a conceptually sound hydrological model is used. Additional uncertainty is introduced in estimating impacts on groundwater recharge, water quality, or flooding/drought as translation of climate into response is less well understood (Arnell, 2004). Uncertainties in climate change impacts on the hydrologic cycle and water resource base are discussed in more detail later in this report (also refer Box 2.3).

Runoff and river discharge

The most dominant climatic drivers for runoff and river discharge are precipitation, temperature and evaporative demand (IPCC, 2007a). Changes in the volume, timing and

Box 2.3 Primary sources of uncertainty in projections of hydro-climatic change

Uncertainties in projected changes in the hydrological systems due to climate change arise from a number of sources. These include the uncertainties in the internal variability of the climate system; uncertainty in future greenhouse gas and aerosol emissions (and, importantly, the populations, levels of economic development, and technologies that generate them); the translation of these emissions into climate change by global climate models; and model uncertainty. Further uncertainties in hydrological projections arise from the structure of current climate models. Current models generally exclude some feedbacks from vegetation to climate change. Most simulations used for deriving climate change projections also exclude anthropogenic changes in land cover.

Incorporating climate model results in freshwater studies also adds uncertainties, which are associated with the different spatial scales of climate models and hydrologic models and biases in long-term mean precipitation as computed by global climate models for the current climate. Methods that have been used to address the scale differences – including dynamical or statistical downscaling methods – introduce uncertainties into the projection. Methods to address biases in simulated mean precipitation do not take into account inter-annual or day-to-day variability in climate parameters and, therefore, risk underestimating future floods and droughts. (Bates, et al, 2008).

intensity of precipitation, and whether precipitation falls as snow or rain, have an impact on river flows. Temperature is particularly important in snow-dominated basins and in coastal areas (due to the impact of temperature on sea level rise). Changes in potential evapotranspiration can offset small increases in precipitation and aggravate further the effect of decreased precipitation on surface waters. Different catchments respond differently to the same changes in climatic drivers, depending largely on catchment physiogeographical and hydrogeological characteristics and the amount of lake or groundwater storage in the catchment (Kundzewicz, et al., 2007).

At the global scale, there is evidence of a broadly coherent pattern of change in annual runoff, with some regions experiencing an increase, particularly at higher latitudes, and others a decrease, for example, parts of West Africa, southern Europe and southern Latin America (Bates, et al., 2007). However, attribution to long-term climate change is difficult because of natural variability and the potential influence of non-climatic factors, such as land use changes. There is more robust and widespread evidence that the ***timing of river flows*** in many regions where winter precipitation falls as snow has been significantly altered due to rising temperatures. World Bank (2009) indicate that climate change is expected to alter the surface hydrology of Peru as a result of changes in hydrology and runoff from the Andean lakes and mountain wetlands—a major source of water for hydropower, urban water supply systems and agriculture—have been impacted by climate change.

Several hundred studies of the potential effects of climate change on river flows have been undertaken, but many of these are regional and heavily focused towards Europe, North America, and Australasia. Of the global scale assessments, Milly, et al., 2005 is one of the most frequently cited. Figure 2.2 shows the mean runoff change until 2050 for the SRES A1B scenario from an ensemble of twenty-four climate model runs (from twelve different GCMs). As shown in the figure, total annual river runoff globally is projected to increase, although there is considerable variability across regions with significant decrease in mid-latitudes and some parts of the dry tropics and significant increase in high latitudes and wet tropics.

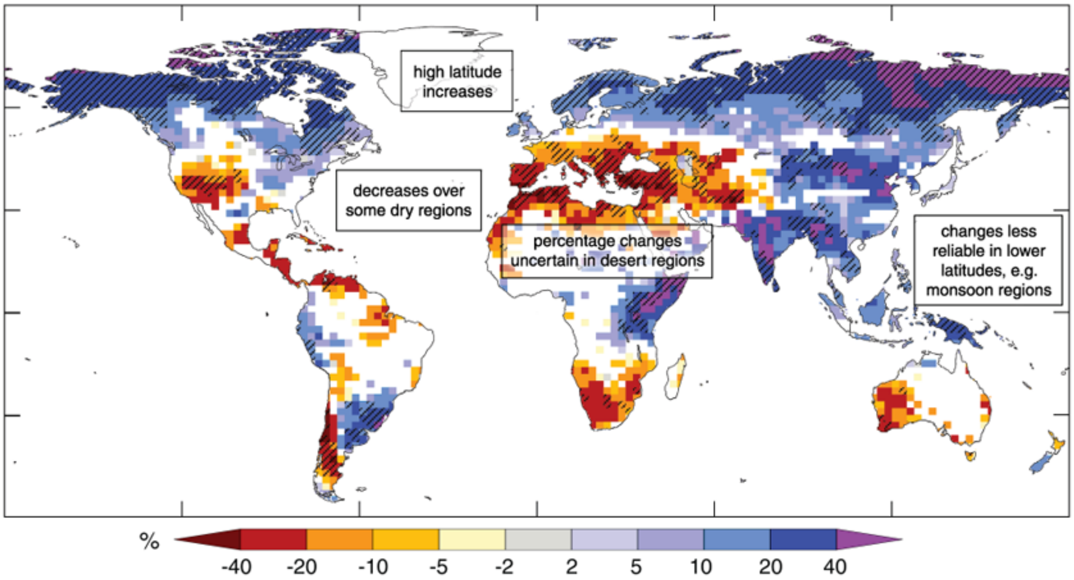
Patterns depend primarily on changes in the volume and timing of precipitation, and whether precipitation falls as snow or rain. In areas *where precipitation currently falls as snow*, a very robust finding, consistent across a number of studies, is that warming would lead to changes in the seasonality of river flows. In *areas fed by glaciers*, higher temperatures would lead to increased river run-off and discharge peaks in the short term, but the contribution of glacier melt would gradually diminish over the next few decades. In areas *with little or no snowfall*, changes in runoff are much more dependent on changes in rainfall than in temperature. A general conclusion of studies is that flow seasonality would increase, with higher flows in the peak flow season and either lower flows during the low flow season or extended dry periods (Kundzewicz, et al., 2007).

Groundwater

Groundwater and soil moisture collectively account for over 98% of the available global freshwater resources. Groundwater levels correlate more strongly with precipitation than with temperature, but temperature becomes more important for shallow aquifers and in warm periods (Kundzewicz, et al., 2007).

In contrast to surface water systems, climate-related changes in groundwater levels have neither been well studied nor adequately observed. This is due to the neglect of groundwater

Figure 2.2 Large-scale relative changes in annual runoff (water availability, in percent) for the period 2090–2099, relative to 1980–1999



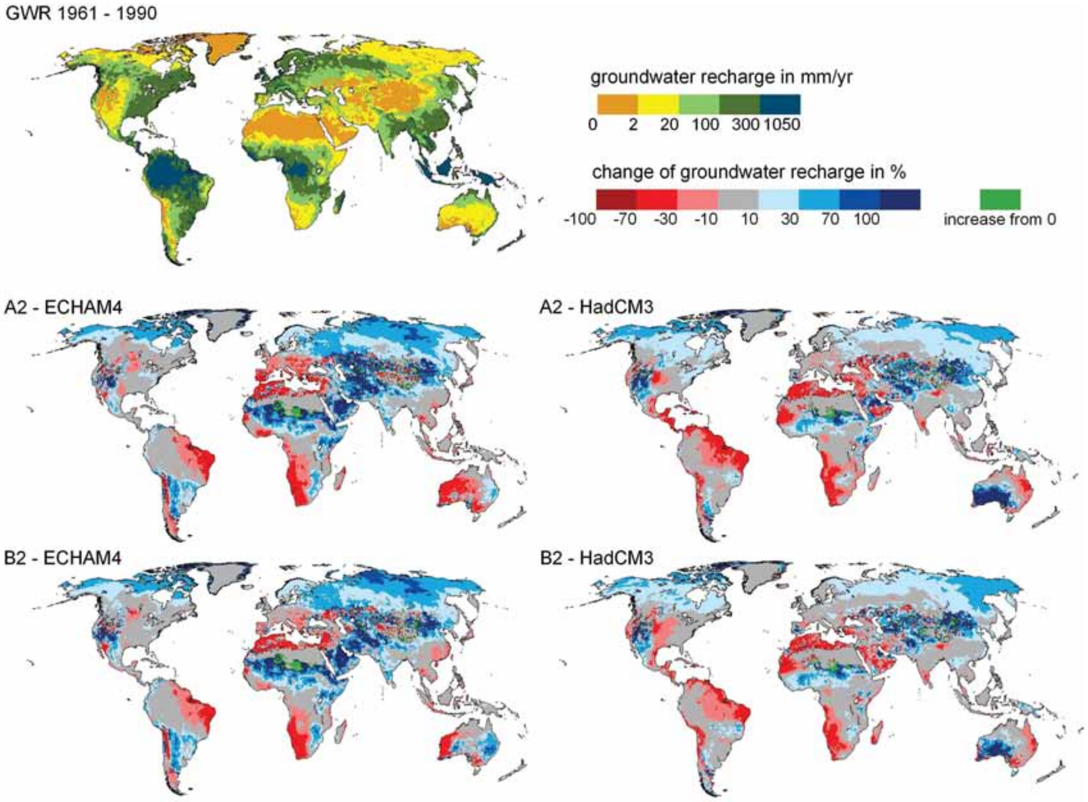
Values represent the median of 12 climate models using the SRES A1B scenario. White areas are where less than 66% of the 12 models agree on the sign of change and hatched areas are where more than 90% of models agree on the sign of change. The quality of the simulation of the observed large-scale 20th century runoff is used as a basis for selecting the 12 models from the multi-model ensemble. The global map of annual runoff illustrates a large scale and is not intended to refer to smaller temporal and spatial scales. In areas where rainfall and runoff is very low (e.g. desert areas), small changes in runoff can lead to large percentage changes. In some regions, the sign of projected changes in runoff differs from recently observed trends. In some areas with projected increases in runoff, different seasonal effects are expected, such as increased wet season runoff and decreased dry season runoff. Studies using results from few climate models can be considerably different from the results presented here. Source: Milly, et al., 2005; IPCC, 2007b, page 49, Fig. 3.5.

management in general as well as due to the hidden nature of groundwater, the very slow reaction of groundwater systems to changing conditions, and measurement difficulties. There is an observed decreasing trend in groundwater levels during the last few decades, but this has been attributed to over-extraction (groundwater pumping exceeding recharge rates).

Critical threats to groundwater as a result of climate change include:

- reduced groundwater recharge—as the result of reductions in precipitation, changes in its seasonal distribution and/or changes in the distribution of precipitation between rainfall and snow. The magnitude of change in groundwater recharge will vary, dependent on local conditions. In some areas, rainfall may fall below the threshold required for any recharge to occur;
- a rapid shift towards increased utilization of groundwater as surface waters become less reliable in selected parts of the world;
- contamination of coastal aquifers and contraction of freshwater lenses on small islands—due to salt water intrusion as sea level rises, coupled with contamination by more extensive storm surge incursions. Salinisation of shallow aquifers could also result from increased evapotranspiration, particularly in semi-arid and arid regions.

Figure 2.3 Global estimates of climate change impact on groundwater recharge



Impact of climate change on long-term average annual diffuse groundwater recharge. Percent changes of 30-year averages groundwater recharge between 1961–1990 and the 2050s (2041–2070), as computed by WGHM applying four different climate change scenarios (climate scenarios computed by the climate models ECHAM4 and HadCM3, each interpreting the two IPCC greenhouse gas emissions scenarios A2 and B2). Source: Döll (2009), Figure 1, page 6.

Relative to surface water supplies, there have been very few studies on the future impacts of climate change on groundwater or on groundwater/surface water interactions. According to the results of a global hydrological model, groundwater recharge, when averaged globally, increases less than total runoff (Doll and Florke, 2005). While the distribution of impact is uneven, the projections suggest that by 2050 there may be significantly less recharge (up to 70% less) in north-eastern Brazil, western southern Africa and along the southern rim of the Mediterranean Sea (See Figure 2.3). Recharge may increase in some areas where rainfall is projected to increase substantially. In some locations where groundwater resources are already stressed, this may help to relieve pressures on groundwater and surface water resources. However, in areas where water tables are already high, increased recharge might lead to problems of soil salinisation and waterlogging. The very few studies of the impacts of climate change on individual aquifers show very site specific results.

Water quality

There is relatively little information on water quality, although a climate-related warming of lakes and rivers has been observed over recent decades. This has led to changes in species composition, organism abundance and productivity, and phonological shifts in some freshwater ecosystems. Higher water temperatures have been reported in lakes in response to warmer conditions, prolonging stratification and depleting oxygen in deeper layers. Consistent climate-related trends in other water quality parameters (e.g., salinity, pathogens, or nutrients) in lakes, rivers or groundwater have not been observed. Likewise, there is no evidence of climate-related changes in erosion and sediment transport (Bates, et al., 2008).

According to IPCC and based on a number of studies, higher water temperatures and changes in extremes, including floods and droughts, are projected to affect water quality and exacerbate many forms of water pollution (IPCC rating: high confidence)**.** More specifically, the following potential effects have been noted:

- Increased water temperatures would impact oxygen solubility, stratification, mixing, and other biochemical processes in lakes and reservoirs, as well as the assimilative capacities of rivers to breakdown organic wastes.
- Increased precipitation intensity would, on the one hand, increase dilution, but would, on the other, potentially increase sediment loads (via increased erosion), nutrients, pathogens and toxins transported to downstream water bodies.
- Longer periods of low flows would reduce the dilution capacity, reduced dissolved oxygen, increase algal blooms, and magnify the impact of water pollution, effecting human health, ecosystems, and water supplies.
- Reduced lake levels may lead to re-suspension of bottom sediments and nutrient cycling.
- Sea level rise could increase saltwater intrusion in estuaries and coastal aquifers, and may also interfere with storm water drainage and sewage disposal.

Floods and droughts

There are a number of climatic and non-climatic drivers influencing flood and drought impacts, and the terms 'flood' and 'drought' capture a wide array of meanings reflecting these different influences. Floods include river floods, flash floods, urban floods, sewer floods, glacial lake outburst floods, and coastal floods (Bates, et al., 2008). 'Drought' may refer to meteorological drought (precipitation well below average), hydrological drought (low river flows and water levels in rivers, lakes and groundwater), agricultural drought (low soil moisture) and environmental drought (a combination of the above) (Kundzewicz, et al., 2007).

Although floods depend on a number of non-climatic factors (including, for example, existence of dams or dykes), there are indications that climate change might already have had an impact on their intensity and frequency. Globally, the number of great inland flood catastrophes during from 1996–2005 is twice as large, per decade, as between 1950 and 1980 (Bates, et al. 2008). This has been associated with an increasing frequency of heavy precipitation events; no ubiquitous increase is visible in trends in high river flows.[8]

Since the 1970s, droughts have also become more common, especially in the tropics and sub-tropics. IPCC concluded that it is *likely* that the area affected by drought has increased since the 1970s, and it is *more likely than not* that there is a human contribution to this trend. That more regions are experiencing drought—as measured by the Palmer Drought Severity Index—is associated with decreased precipitation and increased temperature, which increase evapotranspiration and reduce soil moisture.

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[8] Milly, et al. (2005) found an increase in the frequency of 'large' floods (return period greater than 100 years) across the globe from an analysis of data from large river basins, but other studies have not found a similar trend.

As discussed above, the frequency of heavy precipitation events is projected to increase over most regions throughout the 21st century, which could have a direct impact on flood events. Milly, et al. (2005) found that for fifteen out of sixteen large basins worldwide, the control 100-year peak volumes of monthly river flow are likely to be exceeded more frequently for a quadrupling of CO_2 levels. In some areas, what is given as a 100 year flood now (in the control run) is projected to occur more frequently, even every 2 to 5 years (Bates, et al., 2008; Kundzewicz, et al., 2007). Based on climate models, the area flooded by Bangladesh is projected to increase by at least 23–29% with a global temperature rise of 2 degrees (Bates, et al, p. 52).

According to IPCC, it is *likely* that the area affected by drought will increase (Bates, et al.,2008). One study found that the proportion of the land surface experiencing extreme drought at any one time, the frequency of drought events, and the mean drought duration were projected to increase by the 2090s by 10- to 30-fold, two-fold, and six-fold, respectively (Bates, et al., 2008). In the low-flow season, droughts in snow-melt fed basins may increase due to earlier and less abundant snowmelt. Increased drought is also projected for regions heavily dependent on glacial-melt water for their main dry-season water supply.

Freshwater ecosystems

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

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. Humans generally avoid freshwater for drinking or cooking if it has excessive levels of dissolved minerals or has a very high or low pH. *The changes in water quality (noted above) will contribute to changes in ecosystem composition, function and services, altering the resiliency of ecosystems.* Higher water temperatures in lakes will impact lake productivity and distribution of fish and flora, and exacerbate algal blooms, and may lead to odor and taste problems in drinking water. Droughts will worsen incidence of diarrheal and other water-related diseases, especially in developing countries (WWF, 2009).

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). At a global scale, precipitation is tending to fall in fewer but more intense events, resulting in generally more precipitation. At local scales, there is wide variation. The most striking changes in water quantity often occur with precipitation extremes like 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. The occurrence of precipitation extremes is expected to increase globally, as well as the severity of extreme events themselves (WWF, 2009).

Water timing or seasonality of flows is the expected or average variation in water quantity over some period of time, usually reported as a single year in a hydrograph. Many terrestrial and most aquatic species are extremely sensitive to water timing. Natural selection has adapted (in an evolutionary sense) the behavior, physiology and developmental processes of many aquatic organisms to particular water timing regimes, such as spawning during spring floods or accelerated metamorphosis from tadpole to adult frog in a rapidly drying wetland. Shifts in water timing mean that there may be detrimental mismatches between behavior and the aquatic habitat. In turn, these shifts can affect fisheries stocks and industries that depend on seasonal water flows (WWF, 2009).

CHAPTER 3:
IMPACT OF CLIMATE CHANGE ON WATER AVAILABILITY AND USE

Climate change could profoundly alter future patterns of both water availability and use, thereby increasing levels of water stress and insecurity, both at the global scale and in sectors that depend on water. Indeed, there is already evidence that the impacts of hydrologic change and increased variability are already being felt and that even small changes (e.g., in the magnitude of extreme events) can have exponential losses (see Chapter 4). This said, it should be emphasized that climate change is just one of many factors determining future patterns of water availability and use.

Climate change is expected to increase global water stress and insecurity

Climate change has the potential to increase existing levels of global water stress and insecurity—in terms of both surface and groundwater supplies—and to negatively impact water dependent sectors, from health to agriculture, transport to industry, and energy to ecosystems. Indeed, *the IPCC concluded with high confidence that, globally, the negative impacts of future climate change on freshwater systems are expected to outweigh the benefits.* More specifically, the negative effects of increased precipitation variability and seasonal runoff shifts, water quality and flood risks are projected to outweigh benefits from increased annual runoff overall. It is important to emphasize, however, that projections of water stress are based on certain assumptions about future driving forces—both climatic and non-climatic—as well as water resource management and delivery systems. Many assume—in line with the IPCC's projections—increasing water use, primarily as a result of population and income growth, but also partly due to climate change in the case of irrigation. Additionally, they largely take as given current water systems, including infrastructure, institutions and technology, which will in actuality have a major influence on water availability and use patterns.

Surface water stress assessments

The potential climate-induced changes in hydrology may aggravate global 'water stress.' Most studies have found that levels of water stress will increase as a result of climate change, although the influences of other factors—demographic, socio-economic, and technological changes—are even more significant, particularly in shorter time horizons (impacts beyond the 2050s are highly dependent on the population projections of the emissions scenario used). There are large differences in estimates across studies, depending not only on how climate change impacts are modeled, but also on which other drivers are included in the assessment. Arnell (2004)—who accounts for population growth and the impact of climate change—found that the number of people projected to experience an increase in water stress is between 0.4 to 1.7 billion in the 2020s and between 1 and 2.7 billion in the 2050s (using the A2 population scenario for the 2050s).[9]

In terms of global water availability per capita, climate change would appear to reduce water stress, as projected increases in runoff are concentrated in the most populous parts of the world (mainly East and South-East Asia). Further, in the 2050s, differences in population projections were found to have a larger impact on the number of people living in water stressed basins than climate change, *per se* (Kundzewicz, et al., 2007).

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[9] Where water stress is defined as basins with per capita water withdrawals of less than 1000 m^3/year.

Alcamo, et al. (2002) assessed water stress as a function of population growth and climate change, in addition to changes in water use and other non-climatic drivers (income, water use efficiency, water productivity, industrial production). Water stress was found to increase on 62–76% of the land area and to decrease on 20–29% by the 2050s.[10] Increased water availability due to increased precipitation is the main cause for decreasing water stress; growing water withdrawals (stimulated more by income growth than by population growth) is the main cause of increasing water stress. When environmental flow needs are incorporated—that is, the amount of water required to sustain a functioning ecosystem—the degree of water stress is projected by some to increase further (Smakhtin et al, 2003). There is substantial agreement across these and other global and national-scale assessments that semi-arid and arid basins are the most likely to experience water stress. If precipitation decreases, irrigation water use—which dominates in most semi-arid river basins—would increase, placing additional pressure on other uses.

Groundwater stress assessments

Use of groundwater varies with the quality and availability of the resource, as well as with access to and the reliability of surface water. In developing and developed countries alike, it contributes to human health and socio-economic development through the provision of a low cost and often high quality water resource that is somewhat independent of short-term climatic variability. Over half of the world's population are thought to depend on groundwater for every day uses, such as drinking, cooking and hygiene. Across the developing world, groundwater accounts for between about 20 and 40% of total water use. Agriculture is the dominant use of both groundwater and surface water across the developing world. Groundwater also plays a fundamental role in sustaining many terrestrial, aquatic and even marine ecosystems. For some ecosystems, there is a highly specialized dependency on groundwater, with groundwater being the habitat, the only water supply, or being critical to survival during periods of seasonal water shortage or extended episodes of drought.

The hidden nature of groundwater, its resilience in the face of short-term climatic variability and the difficulty in measuring it, have, among other factors, contributed to its poor management and the growing stress on groundwater resources. In many countries, even developed countries with robust surface water management arrangements, groundwater use is unregulated and poorly planned and managed. Although data on the 'health' of groundwater systems at a global level is scant, what is available demonstrates the challenges it faces. In several countries in North Africa and the Middle East, groundwater allocations exceed average annual recharge by a factor of three times or more. Other developing and developed countries have many zones where groundwater resources have been depleted (Figure 3.1). Consequences of this have already included supply shortages, subsidence, contamination and decline in groundwater dependent ecosystems. As stresses on surface water increase—due to both non-climatic and climatic forces—it is expected that pressure on groundwater resources will grow.

Water security

Aggregate indices of water stress—of the type presented above—are typically in terms of annual averages, and so cannot fully capture the global impacts of hydrological

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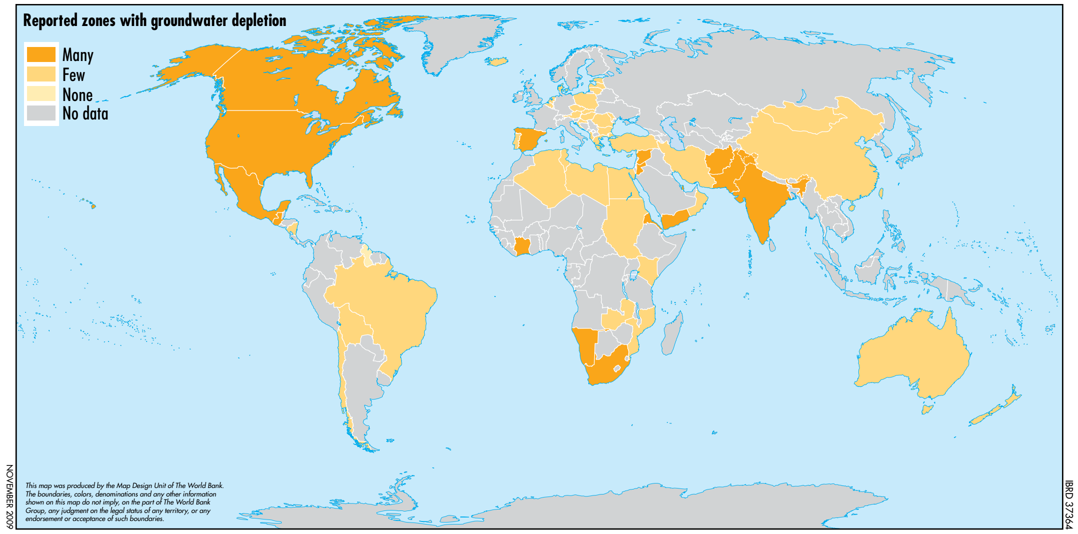
[10] Water stress expressed as the water withdrawal-to-availability ratio.

Figure 3.1 Reported countries with groundwater depletion



Source: IGRAC Global Groundwater Information System [http://igrac.nitg.tno.nl/ggis_map/start.html]

variability and extremes. Many regions of the world have, what has been loosely termed, a 'difficult hydrology'. This includes not only those areas that confront absolute water scarcity (or 'stress'), but also those which suffer from high inter-annual and/or intra-annual hydrologic variability (including extremes). In the absence of adequate capacity, infrastructure and institutions required to manage and mitigate such difficult hydrologies, 'water security' is threatened. Water security is defined as the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments, and economies. Unlike in the case of 'water stress,' a comprehensive assessment of global levels of water security has not been undertaken. However, several regions of the world can be characterized as being water insecure, either because of extreme hydrological variability (e.g., Ethiopia) or a poor endowment of water resources (e.g., Yemen, which is heavily dependent on limited groundwater), or because of the dearth of adequate capacity, infrastructure or institutions. Climate change—which is projected to reduce water availability in regions that are already scarce (as discussed above) and increase hydrologic variability—is likely to make water security harder to achieve and maintain.

Transboundary basins

Over 270 international rivers are shared by some 90% of the world's nations and territories. Transboundary river basins and shared rivers present both challenges and opportunities for cooperation and growth. Developed economies, in Europe and North America, have in most cases achieved a relative equilibrium in managing transboundary basins for best return on hydrology through transboundary institutional arrangements, including treaty regimes dealing with issues of river infrastructure and the quantity and quality of water flows, as well as infrastructure to manage variability and extreme events. Increasingly, cooperative efforts are focusing on the sharing of benefits, rather than water. The developing economies sharing river basins remain challenged by weak institutional arrangements and inadequate infrastructure for optimum benefit. Regardless of the level of economic development, climate change poses a threat to transboundary basins. Evidence suggests that the challenges and conflicts among the riparian states depend on the degree of variability and uncertainty associated with the resource availability. Projected changes in water resources variability due to climate change can impact the water balance and consequently the hydropolitical balance in transboundary basins. Wolf et al (2003), indicate that historically extreme events of conflict over water have been more frequent in water scarce regions and where extreme conditions characterized by high inter-annual hydrologic variability occur.

Water dependent sectors and climate-induced hydrologic changes

In the future, climate change could also impact water using sectors, affecting both the amount and/or quality desired (on the demand side) and/or the extent to which demands are met (on the supply/availability side).[11] The term 'water dependent sectors' is taken broadly to mean both water using sectors (including in-stream and out-of-stream, consumptive and non-consumptive), as well as sectors that are affected indirectly or directly by the water sector (e.g., health and transport). In most countries water use has increased in recent decades due to, amongst others, population and economic growth and changes in lifestyle (including diets). Sectoral water use patterns can be expected to continue to change over time in response to such non-climatic drivers, in addition to water resource management and delivery systems (as discussed above). This includes not only infrastructure and technology, but also institutions that govern water use within sectors (e.g., water pricing), amongst sectors (e.g., water trading), and even across national boundaries (e.g., transboundary river basin agreements). It is important to emphasize that changes in variability could be as important as changes in long-term averages, particularly if water is not withdrawn from groundwater bodies or reservoirs.

The potential impacts of climate change could extend beyond the water sector, *per se*, to all sectors that are linked to (or in some way dependent on) water. For example, pressure on water supply and sanitation facilities could have a wide range of adverse effects on human health. Reduced availability of water for irrigation could threaten food security, rural development, and the economies of countries that are largely dependent on the agricultural sector. The potential impact of climate-driven hydrologic change and increased variability for some key water dependent sectors is discussed below.

Health

Water is essential to human health and all aspects of livelihood. Table 3.1 shows the linkage between mediating climate change factors and their health outcome. An estimated 2.4 billion people are without access to proper sanitation and 1 billion without access to safe drinking water. With projections of potential decreases in water availability, these statistics are likely to get worse. Decreasing water supplies could also lower the efficiency of wastewater and sewer systems, leading to higher concentrations of bacteria and other micro-organisms in raw water supplies (Kabat et al., 2003).

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[11] The agricultural sector offers a good example of the effects of climate change on both water demand and water supply. Increasing CO_2 concentrations could increase water use efficiency for some types of crops, thereby reducing the demand for irrigation (often referred to as irrigation 'requirements'). On the supply side, increased variability could affect the reliability/availability of irrigation supplies.

Table 3.1 Mediating processes and potential effects on health of changes in temperature and weather

Mediating processes	Health outcome
Direct effects	
Change in the frequency or intensity of extreme weather events, for example storms, hurricanes, cyclones	Deaths, injuries, psychological disorders, damage to public health infrastructure
Indirect effects	
Changed local ecology of water borne and food borne infective agents	Changed incidence of diarrheal and other infectious diseases
Changed food productivity (especially crops) through changes in climate and associated pests and diseases	Malnutrition and hunger, and consequent impairment of child growth and development
Sea level rise with population displacement and damage to infrastructure	Increased risk of infectious disease, psychological disorders
Social, economic, and demographic dislocation through effects on economy, infrastructure, and resource supply	Wide range of public health consequences mental health and nutritional impairment, infectious diseases, civil strife

Source: Kabat et. al., 2003 pg. 33; adapted from McMichael and Haines, 1997.

In addition to drinking water and sanitation, there are also water and vector borne diseases that are affected by climate change via the water sector. Water plays a role in propagating diseases by direct transmission (contamination by feces, urine or bacteria), inadequate personal hygiene, and parasites using hosts in or near the water. Decreases in available supply and also floods can increase contamination. Warming temperatures can increase the presence of vector borne diseases such as malaria causing higher transmission rates and new regions to become infected.

There are also direct health effects from extreme events such as floods and droughts which include changes in mortality and morbidity. Projections show an increase in extreme events which translates into real losses of livelihoods and lives. Some indirect effects from floods include overburdening of wastewater and sewer systems, disruption of safe water supply, standing water in low-lying areas (increase in mosquitoes and risk of malaria), exposure to respiratory and infections, disruption and increased burden to medical facilities, and inadequate nutrition following disruption to incomes and food distribution systems. An example of climate change's impact on malaria in Africa is described in Box 3.1.

Box 3.1 Malaria in Africa under climate change

Results from the Mapping Malaria Risk in Africa project (MARA/ARMA) indicate changes in the distribution of climate-suitable for malaria by 2020, 2050 and 2080. By 2050, and continuing into 2080, a large part of the western Sahel and much of southern-central Africa is shown to be likely to become unsuitable for malaria transmission. Other assessments, using sixteen climate change scenarios, show that, by 2100, changes in temperature and precipitation could alter the geographical distribution of malaria in Zimbabwe with previously unsuitable areas of dense human population becoming suitable for transmission. (Bates et al 2008).

Indirect health threats of climate change include malnutrition from agriculture disruption, infectious diseases spread by insects and other vectors advantaged by climate change, as well as the increased risk of infectious diseases due to infrastructure damage (Kabat et al., 2003). Climate changes that would adversely affect human health via the water sector are expected to fall disproportionately on the poor (IPCC 2001).

Agriculture

Agriculture is by far the largest user of water, accounting for almost 70 percent of global withdrawals—and 90 percent of global consumptive water use—and up to 95 percent of withdrawals in developing countries. While a person may drink 2–4 liters of water a day, it takes 2,000–5,000 liters of water to produce a person's daily food. Water is important for food security, crop growth, livestock, and food markets. Food security, defined by the Food and Agriculture Organization (FAO) as the regular access of people to enough high-quality food to lead active, healthy lives, depends heavily on water. Lack of water can be a major cause of famine and undernourishment, especially in areas where people depend on local agriculture for food and livelihoods. Erratic rainfall can cause temporary food shortages, while floods and droughts can lead to intensive food emergencies.

Climate change can significantly impact crop growth. Changes in precipitation can alter soil moisture content, which can lead to conditions that are potentially too dry or too wet for viable crop growth and alter the need for and timing of irrigation. Precipitation changes can occur via extreme events (floods or droughts), erratic rainfall, or seasonal shifts in runoff. There are critical stages in a crop's growth (e.g. filling of the corn kernels) where a lack of water during that short time can reduce crop yield. Rainfed agriculture—which supplies over 60 percent of the world's food—is particularly at risk.

In addition to precipitation changes, increased CO_2 levels and higher temperatures can affect crop growth. Some crops may actually benefit from increased CO_2 levels, while other plants will not. In general, higher temperatures are associated with higher radiation and higher water use which could put stress on overall water availability. It is expected that higher temperatures will promote more plant growth at high latitudes and altitudes (northern regions of former Soviet Union, Canada, and Europe). The higher yields are primarily due to longer growing season and mitigating the negative cold weather effects on plant growth (Kabat et al., 2003). Northern middle latitude countries (US, Western Europe, and most of Canada) are expected to see negative effects on crop and livestock productivity due to increased temperatures and increased evapotranspiration (shortening of the growing season). Taken together, higher temperatures and increased variability of precipitation would, in general, lead to increased irrigation water demand, even if total precipitation during the growing season remains the same (Bates, et al., 2008).

Food markets are affected by climate change. As mentioned previously climate change and variability can lead to decreases in food production. These shortfalls create market imbalances, which push international prices upwards and provide incentives for reallocation of capital and human resources, thus reducing climate-change impacts by economic adjustments. The GDP of the agricultural sector in developing regions, with the exception of Latin America, will be negatively impacted by climate change (Kabat et al., 2003.) This is due to the lack of high-tech solutions that can meet the needs of the poorer farmers, who most often partake in rainfed agriculture.

Key drivers for future irrigation water demand are the extent of irrigated area, unit water use, cropping intensity, and irrigation water-use efficiency. According to the Food and Agriculture Organization (FAO) agriculture projections for 2030 suggest that developing countries are likely to continue to expand their irrigated area and to increase cropping intensity (e.g., double cropping) while irrigation water-use efficiency will increase slightly. Climate change will worsen these estimates. Most of this expansion is projected to occur in already water-stressed areas, such as southern Asia, northern China, the Near East, and North Africa. After 2050, the irrigated area is assumed to stabilize or to slightly decline in most cases.

Industry and transport sector

Many industries depend on water to create their product. Beverage companies require a reliable source of water that meets a strict quality. Other industries use water in their manufacturing process. Some power industries use water for cooling. The ski industry relies on snowpack/glacier stability for operation which can be directly affected by climate change. Changes to the availability of water will greatly affect the success of these industries. Most of the industries will release the water after they have used it into streams for future use. There is a certain standard that the effluent from the industry must meet both in temperature and quality. Predictions of lower stream flows would have a major effect on effluent standards. Industries would have to spend more time and money producing higher quality effluent to meet standards.

Transport sector has close links with the water sector. Transportation via water is directly affected by water levels in navigable rivers. Decreases in river flow will potentially reduce and/or eliminate transportation via waterways. Other transportation means including roads and bridges and railways and subways will be most affected by extreme events such as flooding. Impacts on transportation have a direct affect on livelihoods; including the ability for people to get access to necessary food and water, and make a living.

Energy/Hydropower

Hydropower generation is the energy source most likely to be impacted by climate change and climate variability because it directly deals with water quantity and timing. An example of hydropower being negatively impacted by climate change is described in Box 3.2 for the Zambezi basin. A side note on climate change's impact on the demand for energy is that while it is likely there will be an increased energy demand for space cooling due to higher summer temperatures, there will also likely be a decreased energy demand for space heating due to higher winter temperatures (Kabat et al., 2003).

A reduction in river flow results in a decrease in hydropower production. First because there is less water going through the turbines and second because the lower water levels reduce the water pressure and the amount of power that can be produced. While hydroelectric projects are designed for a specific flow regime, including a margin of safety; projected climate changes are expected to change those flow regimes, in some instances to a point outside the current safety margins. This will result in a need to retrofit current structures or tear down and build new hydroelectric projects. With more intense rainfall events as suggested in climate projections, more conservative water storage strategies will be necessary to prevent flood damage resulting in a decrease in using full hydropower potential because reservoirs will not be kept full. The projected increase in droughts will also require more conservative water storage strategies and may decrease the amount of water available to release for hydropower. Lastly, with less precipitation falling as snow, there will be less water available during warm months when energy demand is highest (Kabat et al., 2003).

Natural ecosystems

Freshwater ecosystems are essential components of the environment. Climate change potentially affects the water sector via direct, indirect, and synergistic impacts with non-climate forces. Each of these will have significant impacts on freshwater ecosystems. A change in the variability or trend of climatic conditions also impacts the environment as seen in Southern Africa. Direct impacts of reduced rainfall and increased temperature include lower flows in rivers, lower level in water tables, lower rates of groundwater recharge, and higher temperatures in rivers and lakes. Direct climate change impacts on water quantity, timing, and quality regimes are also expected to affect the performance and operation of existing and planned water infrastructure—including water storage and transfer, hydropower, structural flood defenses, urban drainage, water supply, and irrigation systems.

Box 3.2 Hydropower in Zambezi Basin under climate change

A study of hydro-electric power generation conducted in the Zambezi Basin, taken in conjunction with projections future runoff, indicate that hydropower generation would be negatively affected by climate change, particularly in river basins that are situated in sub-humid regions (Bates et al 2008).

Indirect impacts of the climate changes include the following (Kabat et al., 2003):

- disruption of flowering phenology
- shifts in vegetative season
- species invasions
- changes in productivity of the ecosystem
- shifts in nutrient cycles related to fluctuations in water levels
- changes or declines in hydrological connectivity that can lead to loss of habitat critical to faunal life stages, i.e. fish
- occurrence and/or shifts in intensity and frequency of structuring processes (fire, flood, pests)

In addition, societal responses to anticipated climate threats could indirectly affect aquatic environments through new infrastructure development (e.g., to meet targets for renewable energy and reduce greenhouse gas emissions, or to protect against flooding), and changes in land use (e.g., to adapt to changed growing seasons and/or water availability, or to cultivate new crops such as bio-fuels)[12]**.** Finally, non-climatic pressures on freshwaters linked to population and economic growth, or to land use change, could be amplified by climate change. For example, 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.

Changes to the ecosystem can also impact human livelihoods such as ecotourism and fishing. In addition, ecosystem changes can impact human health. For example, decreasing fish populations can diminish the main, if not only, protein source for a human community.

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12 See for example a sector by sector review for Europe Berry, P., Paterson, J., Cabeza, M. et al. 2008. *Mitigation measures and adaptation measures and their impacts on biodiversity.* Minimisation of and Adaptation to Climate change: Impacts on Biodiversity (MACIS). Oxford University, 320pp.

Impact of non-climatic drivers on water availability and use patterns

Non-climatic factors could aggravate or attenuate the adverse effects of climate change on surface water and groundwater availability, as well as have a significant influence on water use. Population growth, food consumption (including type of diet), economic development (and by extension, changes in lifestyles and societal views on the value of water), technology, and economic policy (including water pricing and trade in 'virtual water') will play a major—if not dominant—role in influencing water use patterns.

Box 3.3 Fate of ecosystems in Southern Africa under climate change

By 2050, the Fynbos Biome (Ericaceae-dominated ecosystem of South Africa, which is an IUCN 'hotspot') is projected to lose 51–61% of its extent due to decreased winter precipitation. The succulent Karoo Biome, which includes 2,800 plant species at increased risk of extinction, is projected to expand south-eastwards, and about 2% of the family Proteaceae are projected to become extinct. These plants are closely associated with birds that have specialized on feeding on them. Some mammal species, such as the zebra and nyala, which have been shown to be vulnerable to drought induced changes in food availability, are widely projected to suffer losses. In some wildlife management areas, such as the Kruger and Hwange National Parks, wildlife populations are already dependent on water supplies supplemented by borehole water (Bates et al., 2008).

Non-climatic factors are likely to have significant adverse effects on surface water and groundwater quality. These could be aggravated by climate change. Industrial development, run-off from agriculture, and un-treated sewerage from agglomerations already impact adversely on the quality of water. The World Bank recently estimated the negative effect of water pollution on GDP in China to be 1% annually, the threat of arsenic pollution in drinking water in Bangladesh and other places has been exacerbated by over extraction. These effects may be aggravated by climate change if flows and groundwater recharge is diminished and/or water demand is increased.

Human activities significantly influence water availability and land use, as well as critically impact the existing and future water resource management and delivery systems. Systems for delivering water services include irrigation; urban water, sanitation and drainage; rural water and sanitation; and ports and navigation. Systems for managing water resources include those for delivery of bulk irrigation water, watersheds, and water resources broadly, as well as multi-purpose systems (including hydropower) and flood control. As indicated earlier, the term 'system' is intended to capture all elements—from infrastructure to institutions—that contribute to performance of the intended function.

The impact of climate change could carry significant negative consequences for existing water resource management and delivery systems. For example, in urban environments, more heavy rainfall events could overload the capacity of storm drain systems and water and wastewater treatment facilities; sea level rise could lead to salinization of water supplies from coastal aquifers. Climate change could increase irrigation demand due to the combination of decreased rainfall and increased evapotranspiration, placing additional pressure on irrigation systems that are in many cases already under performing. Changes in river flows could have a direct impact on hydropower generation facilities. Soil erosion from increased rainfall intensity could affect watershed sustainability and lead to sedimentation in reservoirs, impacting on the operation of multi-purpose facilities. Extreme variability and/or reduced supplies could stretch the infrastructural and institutional limits of systems that manage water across sectors and even national boundaries. Some of the non-climatic factors, as identified by IPCC are given in Box 3.4.

Box 3.4 Non-climatic drivers of change in freshwater systems

In addition to the discussion of hydrologic and climatic impacts, there are also many non-climatic drivers of freshwater systems. For example, water use is driven by changes in population, food demand, economy, technology, lifestyle, and societal views regarding value of freshwater ecosystems. Land use change, construction and management of reservoirs, pollutant emissions, and water and waste water treatment all influence both the quantity and quality of freshwater. Also, water management (i.e., how a reservoir releases water, what demands have priority, etc.) plays a major role in the vulnerability of a water system both at the national and international level (Bates et al 2008).

CHAPTER 4:
THE COST OF VULNERABILITY TO HYDROLOGIC CHANGE AND INCREASED VARIABILITY

The developing world is particularly vulnerable to climate change

The impacts of a changing climate on the hydrologic cycle will be felt in developed and developing countries alike. However, many parts of the developing world are particularly vulnerable. Vulnerability to climate change has been defined by IPCC as the degree to which geophysical, biological and socioeconomic systems are susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. It is a function of, amongst others, the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity. The financial cost of vulnerability is difficult to assess and even more difficult is the cost of adaptation to uncertain future. Work is in progress to address financial costs. Here, the focus is primarily on the non-financial costs.

A number of factors make many developing countries—and the poorest within them—particularly vulnerable to the potentially adverse impacts of climate change. These include weak institutions and limited institutional capacity, high levels of poverty, insufficient stock of water management and services infrastructure, lack of access to technology and capital to invest in risk reduction, and dependence on climate-sensitive sectors such as agriculture, forestry and fisheries. More precisely, several factors, both physical features and societal characteristics, have been associated with high levels of vulnerability (Arnell, 2003). These include:

- Physical Features
  - A current hydrological and climatic regime that is marginal for agriculture and livestock
  - Highly seasonal hydrology as a result of either seasonal precipitation or dependence on snowmelt
  - High rates of sedimentation of reservoir storage
  - Topography and land-use patterns that promote soil erosion and flash flooding conditions
  - Lack of variety in climatic conditions across a region, leading to inability to relocate activities in response to climate change

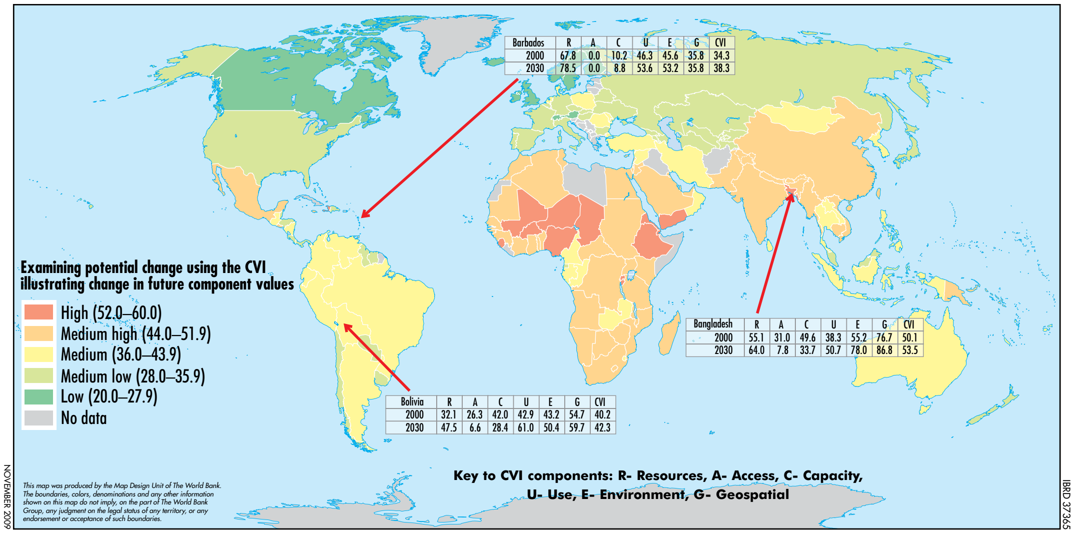
- Societal Characteristics
  - Poverty and low income levels, which prevent long-term planning and provisioning at the household level
  - Lack of infrastructure, or poor maintenance and deterioration of existing infrastructure
  - Lack of human capital skills for system planning and management
  - Lack of appropriate, empowering institutions
  - Absence of appropriate land-use planning
  - High population densities and other factors that inhibit population mobility
  - Increasing demand for water because of rapid population growth
  - Conservative attitudes toward risk (unwillingness to live with some risk as a tradeoff against more goods and services)
  - Lack of formal links among various parties involved in water management

Many, if not all, of the above factors are prevalent in the developing world, and so the implications of climate change are likely to be greatest here. Indeed, this is precisely the finding of the more rigorous 'vulnerability assessments,' which are presented below.

Vulnerability to surface water stress

Several attempts have been made to estimate vulnerability on a global scale. This is done by incorporating some proxy for adaptive capacity ('economic coping capacity', Raskin et.al, 1997; the Human Development Index, Alcamo and Heinrichs, 2002). Perhaps the most comprehensive is the Climate Vulnerability Index (CVI), which is an extension of the Water Poverty Index. Six major components are included in the CVI—resource, access, capacity, use, environment, and geospatial—each of which is comprised of several variables. Figure 4.1 compares vulnerabilities of different regions at present and how they might be affected over the next thirty years. As can be seen, most of the developing world falls in the range of medium to high vulnerability.

Figure 4.1 Some preliminary results for applying the Climate Vulnerability Index (CVI) for comparison of vulnerability by region at present and in 30 years



Barbados	R	A	C	U	E	G	CVI
2000	67.8	0.0	10.2	46.3	45.6	35.8	34.3
2030	78.5	0.0	8.8	53.6	53.2	35.8	38.3

Bangladesh	R	A	C	U	E	G	CVI
2000	55.1	31.0	49.6	38.3	55.2	76.7	50.1
2030	64.0	7.8	33.7	50.7	78.0	86.8	53.5

Bolivia	R	A	C	U	E	G	CVI
2000	32.1	26.3	42.0	42.9	43.2	54.7	40.2
2030	47.5	6.6	28.4	61.0	50.4	59.7	42.3

Source: Sullivan and Meigh, 2005 and Sullivan and Huntingford, 2009

Vulnerability to groundwater stress

A preliminary assessment of the vulnerability of groundwater in World Bank regions to climate change was recently undertaken by the World Bank (World Bank, 2009b). Vulnerability is assessed for 2050, assuming all non-climatic conditions as current. The assessment is at regional scale and is intended as a general indicator only. Four criteria were considered in the regional vulnerability assessment (Table 4.1):

- current level of exploitation of groundwater resources—as indicated by the use of groundwater relative to average annual recharge (after IGRAC, 2004);

Table 4.1 Preliminary assessment of vulnerability of groundwater in World Bank regions to climate change

	Sensitivity	**Exposure**		**Adaptive capacity**	
World Bank region	**Utilisation of groundwater**	**Climate change impact on recharge**	**SLR[1] & storm surge exposure**	**Per capita GNI1**	**Vulnerability[2]**
East Asia & Pacific	Moderate	Increase	Medium	Moderate	Moderate
Europe & Central Asia	Low	Increase	Low	High	Low
Latin America & Caribbean	Moderate	Reduction	Medium	Moderate	Moderate
Middle East & North Africa	High	Uncertain	Low	Moderate	Moderate
South Asia	Moderate	Negligible	High	Low	High
Sub-Saharan Africa	Moderate	Reduction	Low	Low	High

[1] SLR—sea level rise; GNI—gross national income (in $US)

[2] Vulnerability assessed from the sum of average of sensitivity and exposure ratings and adaptive capacity rating.

- Groundwater utilisation—low (2), moderate (4), high (6)
- Impact on recharge—increase (2), uncertain/negligible (4), reduction (6)
- SLR exposure—low (1), medium (2), high (3)
- Per capita GNI—low (6), moderate (4), high (2)—relative to each other

Low vulnerability (<6), Moderate (6–9), High (>9)

Additional Note: Although such a regional scale analysis masks country-to-country differences in vulnerability—which are expected to be large—it provides some insight into potential 'hot spots' of climate change vulnerability.

- the magnitude and trend in changes in rates of groundwater recharge under 2050 climate change projections (after Döll and Flörke, 2005);
- the exposure of regional water resources to sea level rise and contamination due to storm surge (based on the authors' assessment of cyclone incidence, the extent of coastal areas in the region and population density in these areas);
- wealth, as measured by per capita gross national income (GNI; World Bank, 2008[13])

Groundwater utilization is used as an indicator of sensitivity to climate change. The second and third criteria were indicators of exposure and GNI was used to indicate adaptive capacity. These factors were combined to provide a vulnerability indicator. Adaptive capacity and the combination of exposure and sensitivity indicators were weighted evenly. Weighting to sea level rise and storm surge risk was reduced to reflect its uneven application to World Bank regions.

While there remains significant uncertainty with this assessment, it suggests that groundwater in the World Bank Europe and Central Asia region is the least vulnerable to

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[13] Data from http://go.worldbank.org/GKIIAZEJR0

the effects of climate change. This reflects the relatively low level of utilization of groundwater, the projected increase in rainfall (in many areas), minimal exposure of groundwater to risks from sea level rise and storm surge and higher per capita income. Groundwater resources in the South Asia and Sub-Saharan Africa regions were considered to be most vulnerable.

Costs to the most vulnerable

The most vulnerable regions of the world are already suffering huge costs associated with climate and hydrologic variability, and this could be worsened by longer-term changes in climate. In particular, the incidence and severity of both floods and droughts has been growing globally, as have the economic, social and environmental damages associated with them. Yearly economic losses from large extreme events—including floods and droughts—have increased ten-fold between the 1950s and 1990s. From 1990 to 1996 alone, there were six major floods throughout the world in which the number of fatalities exceeded 1,000 and 22 floods with losses exceeding US$1 billion each (Kabat et al., 2003). The developing world—and particularly in South and East Asia—have been the worst hit by disastrous floods. Although part of the increase in losses is attributable to socio-economic factors—including population growth, expansion into flood prone areas, land use changes, manipulation of water within channels—climatic factors are also partly responsible. Droughts have been equally devastating, particularly in Africa, which has been exposed to more recurrent droughts than any other part of the world. Again, non-climatic factors—including poor management of water resources, urbanization and degrading watersheds, and in the worst cases, civil war—have played a significant role in increasing vulnerabilities to drought.

Studies that have assessed the economic impacts of climate variability—and in particular floods and droughts—in the developing world have found these to be substantial. One of the earliest study estimated the cost to Kenya of two extreme events, finding that the 1997/8 El Niño floods cost the country 11 percent of its GDP and the 1998/2000 La Niña drought, 16 percent (World Bank, 2004). According to the study, given their regularity and over the long term, floods and droughts are estimated to cost Kenya about 2.4 percent of GDP annually, and water resources degradation a further 0.5 percent of the GDP annually, representing a serious drag on the country's economy. The calculation of annualized cost was based on the frequency and intensity of historical floods and droughts. As these are likely to become more pronounced with climate change, economic costs can be expected to be even more substantial in the future, all else equal. In Ethiopia, economy-wide models incorporating hydrological variability show that the projections of average annual GDP rates drop by as much as 38 percent, as compared to when hydrological variability is not included (Mogaka et al., 2006). The economy—heavily dependent on rainfed agriculture—was found to be so intimately tied to hydrological variability that even a single drought event within a twelve year period would diminish average growth rates across the entire twelve year period by 10 percent. Both of these cases have 'difficult hydrologies'. However, it is not hydrological variability per se—but extreme vulnerability to it due to a lack of the 'minimum platform' of necessary capacity, infrastructure and institutions to mitigate the impacts—that makes them water insecure. As just one indicator, installed reservoir capacity per capita is only 40 m^3 in Ethiopia (a nation with greater climate variability) as compared to over 6000 m^3 in North America (an area with much less climate variability).

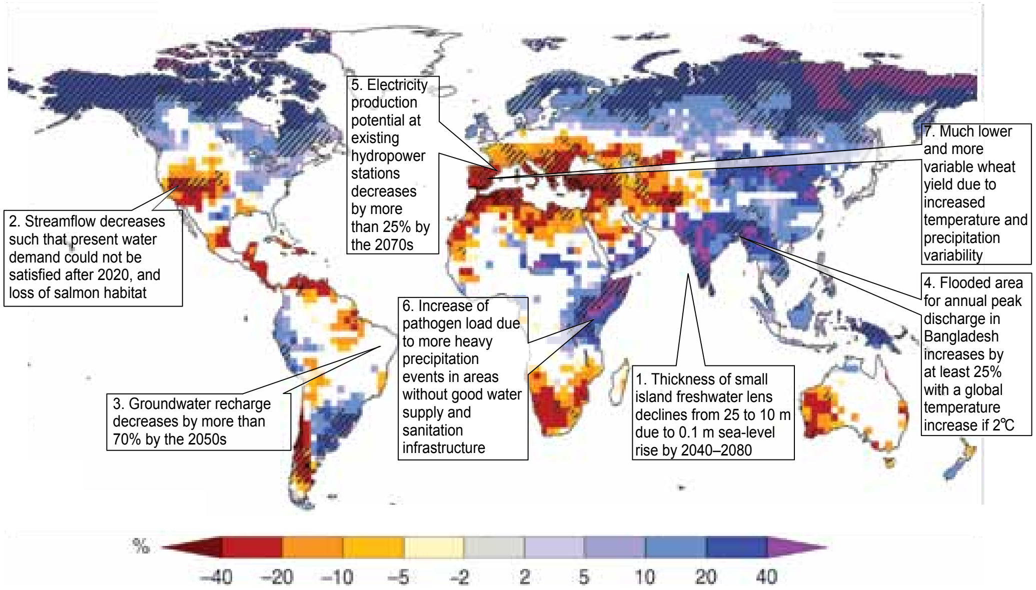
Climate change is projected to alter the amount, intensity and frequency of precipitation, directly affecting not only the magnitude and timing of floods and droughts, but also runoff patterns, groundwater recharge, and water quality. For example, glacial meltdown in several regions of the world—including the Andes and the Himalayas—is already occurring and the rate is projected to increase with a continual warming of the climate. The Himalaya glaciers are reducing at a rate of 33–49 feet per year. Glacial melt is expected to lower water levels in river basins, including the Indus and the Ganges, by as much as two-thirds, affecting over 500 million people in India. On a per capita basis, water availability is projected to decline by over 30 percent in the next four decades. India has one of the world's most ambitious hydropower programs, but there might not be sufficient water available to run the new turbines by the time that the dams are built. India's megacities in coastal areas—such as Mumbai and Chennai—are also at risk. Some experts have estimated that India's GDP could drop by as much as nine percent, largely due to submergence. It is estimated that Mumbai alone could lose up to $48 billion (Tehelka, 2008).

Implications for sustainable development and the Bank's mission for poverty reduction

For regions that are already highly vulnerable to climate variability, the potential impacts on all sectors that depend on water—from domestic water supply and agriculture to health and the environment—could strain economies and livelihoods. In many regions of the globe, climate change may put at risk progress that has been made over several decades in sustainably developing economies and societies. Indeed, according to the IPCC, "even with optimal water management, it is very likely that the negative impacts on sustainable development cannot be avoided" (Bates, et al., 2008). Figure 4.2 shows some key cases around the world where water-related climate change impacts on various sectors and systems are a threat to the sustainable development of affected regions.

The current financial crisis and various sector crises have already and will continue to impact financing of adaptation to climate change. A theme that has been emphasized throughout this report is that climate change is not the only—or even the primary—factor exerting stress on the water sector, and by extension societies, economies, and the environment. The current financial crisis and the sector crises (e.g., rising food prices, energy cost) have forced many governments in developing countries to defer urgent operation and maintenance, as well as water investment needs. This can exacerbate efforts of the governments in tackling their current water challenges, such as provision of safe drinking water and improved sanitation, jeopardizing achievement of the Millennium Development Goals targets. The private sector capital flight is expected to continue in these financially uncertain times, affecting investment decisions with climate adaptation aspects. In the near- to medium-term, the situation is expected to worsen unless investment funds are channeled to the sector. Here, a combination of the new financial and climate change architectures such as the Vulnerability Fund, the Climate Investment Fund, and other mechanisms to alleviate the investment bottle neck should be made available to the client Bank countries. This, at a minimum, can help protect infrastructure assets through coverage of cost of operation and maintenance. Current hydrologic variability and magnitude and frequency of extreme events may make meeting water-related MDGs (targets 1, 6 and 7) by 2015 more difficult. But it is highly unlikely that these alone will hamper achievement. The significance of climate change lies in its interaction with other pressures, both current and future. Making systems, societies and economies less vulnerable to the potential impacts requires that climate change be addressed within this broader context. Viewed in the long term, the current financial crisis and the stimulus packages to respond to this crisis can be designed to take into account the wider risk of climate change in the recovery and rebuilding process.

Figure 4.2 Illustrative map of future climate change impacts related to freshwater which threaten the sustainable development of the affected regions



5. Electricity production potential at existing hydropower stations decreases by more than 25% by the 2070s

7. Much lower and more variable wheat yield due to increased temperature and precipitation variability

2. Streamflow decreases such that present water demand could not be satisfied after 2020, and loss of salmon habitat

4. Flooded area for annual peak discharge in Bangladesh increases by at least 25% with a global temperature increase if 2℃

6. Increase of pathogen load due to more heavy precipitation events in areas without good water supply and sanitation infrastructure

3. Groundwater recharge decreases by more than 70% by the 2050s

1. Thickness of small island freshwater lens declines from 25 to 10 m due to 0.1 m sea-level rise by 2040–2080

1: Bobba et al. (2000), 2: Barnett et al. (2004), 3: Doll and Floke (2005), 4: Mirza et al. (2003), 5: Lehmer et at. (2005) 6: Kistemann et al. (2002), 7: porter and Semenov (2005). Background map: Ensemble mean change of annual runoff, in percent, between present (1980–1999) and 2090–2099) for the SRES A1B emissions scenarios (based on Milly et al., 2005). Areas with blue (red) colors indicate the increase (decrease) of annual runoff. [Bates et al, 2008, Fig. 3.4 pg. 47]

CHAPTER 5:
CLIMATE AND HYDROLOGY PROJECTIONS FOR INVESTMENT DECISIONS

Introduction

The purpose of these projections is to gain insight into potential future hydrology and to establish a common platform of information on the behavior of key hydrologic drivers across World Bank regions at a scale appropriate for policy and investment decisions. The catchment level was selected because it is the most appropriate scale for water planning and investment. Projected impacts on runoff and basin yield, extreme events (floods and droughts), minimum base flow (a proxy for groundwater recharge), and net irrigation demand are assessed here, as these variables are particularly relevant for water planning and investments. The methodological approach used for this analysis was developed to explicitly tackle two difficult issues that plague climate change assessments: (i) how to 'match' model outputs generated at a course resolution with the desired (and typically finer) scale and (ii) how to take advantage of all information generated from climate models, specifically by capturing the full spectrum of model projections. Twenty-two GCMs along with three emissions scenarios (A1B, A2 and B1) are used to analyze changes in the key hydrologic variables in the years 2030 and 2050. For each World Bank region, the wettest, driest and a middle scenario are identified based on the climate moisture index. These scenarios serve as the basis for estimating changes in the key hydrologic variables.

Key issues in climate change impact assessments

Resolution and scale in impact assessments

One potential difficulty with using climate information in impact assessments—including in the water sector—is the 'mis-match' between the low spatial (and temporal) resolution of GCMs, on the one hand, and the scale at which assessments need typically to be conducted for investment purposes, on the other. GCMs provide climate change projections at a low spatial resolution (~2.5° x 2.5° grid; Table 5.1) while water planning and management analyses often require a much finer resolution (~0.5° x 0.5° grid or even finer for project level analyses). Table 5.2 provides a list of areas for 1°grid cells at various latitudes for reference. The goal of the assessment—i.e. what is it trying to answer; who is it trying to inform?—should drive the decision on both the relevant scale, and the most appropriate technique to use for matching GCM output with that scale.

There are several methods available for addressing scale issues, including statistical downscaling (using empirical relationships), dynamical downscaling (using regional climate models) and 'spatial techniques'[14] (linear interpolation, krigging, spline fitting, and intelligent interpolation). Downscaling involves methods used to map the large scale signals from GCMs to a finer resolution (tens of kilometers versus hundreds of kilometers).

Care needs to be taken in selecting the method of analysis. Beyond reproducing the underlying uncertainties of GCMs, many introduce additional uncertainty and biases. For example, downscaling techniques increase the detail of information, but also the uncertainties associated with that information due to fact that the GCM output is manipulated below the scale at which

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[14] 'Spatial technique' is often and commonly referred to as 'spatial downscaling' but technically does not involve downscaling algorithm. The majority of 'downscaling' being done is with this method.

Table 5.1 Spatial Resolution of AR4 IPCC Archived GCMs

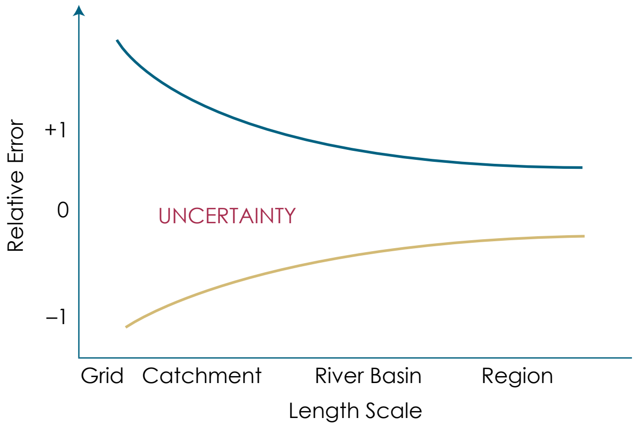
GCM	Latitude	Longitude	Area at 40° lat (km²)
bccr_bcm2_0	2.81	2.81	75,115
cccma_cgcm3_1	3.75	3.75	133,538
cccma_cgcm3_1_t63	2.81	2.81	75,115
cnrm_cm3	2.81	2.81	75,115
csiro_mk3_0	1.88	1.88	33,384
csiro_mk3_5	1.88	1.88	33,384
gfdl_cm2_0	2	2.5	47,480
gfdl_cm2_1	2	2.5	47,480
giss_aom	3	4	113,952
giss_model_e_h	3.91	5	185,792
giss_model_e_r	3.91	5	185,792
iap_fgoals1_0_g	3	2.81	80,123
inmcm3_0	4	5	189,920
ipsl_cm4	2.5	3.75	89,025
miroc3_2_hires	1.13	1.13	12,018
miroc3_2_medres	2.81	2.81	75,115
mpi_echam5	1.88	1.88	33,384
mri_cgcm2_3_2a	2.81	2.81	75,115
ncar_ccsm3_0	1.41	1.41	18,779
ncar_pcm1	2.81	2.81	75,115
ukmo_hadcm3	2.47	3.75	87806
ukmo_hadgem1	1.24	1.88	22,103
Average	**2.6**	**3**	**72,420**

Table 5.2 Coverage area of 1-degree latitude by 1-degree longitude

Latitude	1 Degree Longitude km	1 Degree Latitude km	1 Square Degree e km²
0	111	111	12,393
40	85	111	9,496
60	56	111	6,181
80	17	111	1,876

the physics of the GCM itself are mathematically described. Under some downscaling schemes, mass balances of water and energy over the GCM scale are violated by the downscaling algorithm. Use of dynamical and statistical downscaling techniques requires extensive quantification of the sensitivities of the underlying assumptions of both the GCMs and the downscaling algorithms, resulting in the need for exhaustive numerical experimentation. Time and cost constraints often do not allow use of more than a couple of GCMs in downscaling exercises. Running multiple GCMs at a coarse resolution may provide more insight into the range of possible futures than more detailed information obtained from fewer GCMs.

Figure 5.1 The cone of uncertainty in scale and resolution of modeling



There is no one 'best' method; the most appropriate method for a particular application will strike a careful balance between precision (resolution) and accuracy (confidence in projections). Figure 5.1 provides a visual representation of the trade-off between precision and accuracy. As resolution increases, so does the uncertainty associated with the more detailed information. In other words, more 'precise' information comes at a cost, and the additional uncertainty must be recognized and taken into account in assessing impacts. Given the trade-off, it is critical to establish at the outset of any impact assessment whether the goal is to have finer resolution or 'better' (that is, more reliable) information.

In this analysis, the catchment level is selected as it is the most appropriate scale for water planning and investment. This analysis does not employ dynamical or statistical downscaling techniques for the reasons stated above. Instead, projections from 22 GCMs and 3 SRESs were applied at their native spatial grid scale (~2.5° x 2.5°), and the changes in climate variables between the model runs and the 20th Century runs were applied directly to 0.5° by 0.5° gridded monthly historic climatology. The advantage of this approach is that it allows investigation of all the IPCC GCMs and emissions scenarios at the native spatial resolution, thereby capturing a range of potential climate change impacts and achieving a balance between precision and accuracy.

To reduce the uncertainties inherent in obtaining climate variables at high resolution, the 0.5° by 0.5° gridded data are 're-aggregated' to the catchment level. The average scale of a catchment is approximately the size of the native spatial grid scale of the GCM (~2.5° x 2.5°) which results in less uncertainty in final projections. Figure 5.2 shows the three relevant scales: 0.5° x 0.5° grid, 2.5° x 2.5° grid, and the catchments. The catchments are obtained from the USGS Hydro1K, a geographic database. Hydro1K has six levels of catchments. For this analysis level 4 is selected for all Bank regions except AFR, where level 3 is used. There are 8,406 catchments covering the World Bank regions, which translate into an average of six 0.5° x 0.5° grids per catchment. Using GIS, the catchment boundaries are overlaid with the grids and the cells are aggregated by their weighted area in the catchment.

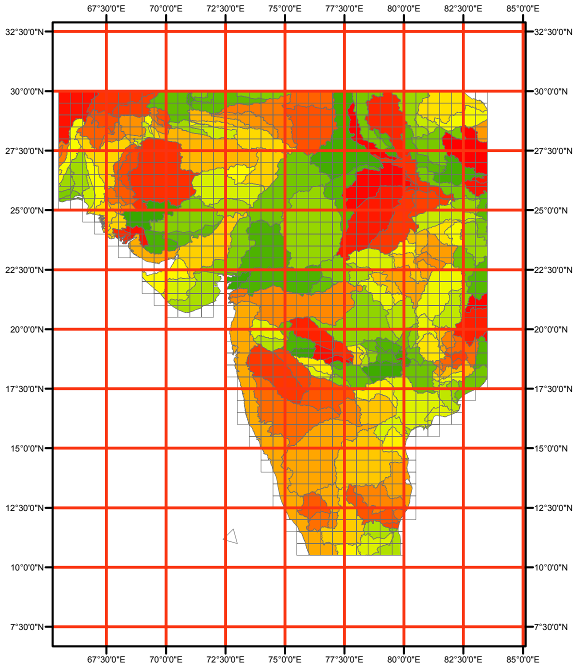


Figure 5.2 Section of the SAR region showing 0.5° by 0.5° grid scale, 2.5° by 2.5° (GCM) grid scale (dark larger grids), and catchment boundaries in color

Generating and capturing climate change projections

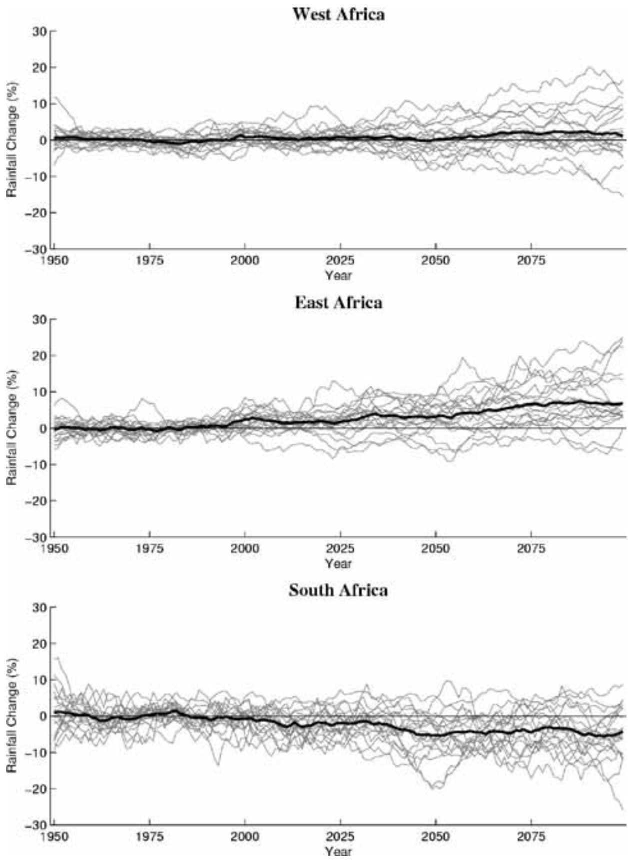
In the context of downscaling, relying on results from a single or a few GCMs is not advisable. This is because there are model errors in any one model and natural variability (randomness) in any particular run. A single model, if run multiple times with differing initial conditions, can provide an estimate of the uncertainty due to natural variability. However, for any given model, there are also uncertainties associated with the assumptions made about model physics and parameterizations, as well as with the structural aspects of the model itself. Using a group of GCMs (multi-model ensembles), as opposed to one individual GCM, can account for biases and errors. The use of multi-model ensembles raises the question of how to capture the full range of results from model runs.

Strong caution is advised when using the mean of multiple models with the rationale that the mean is a good representation of all runs. This can lead to wrong conclusions. The problem with relying on the mean is that it masks extreme values. A model 'average' of near zero could be the result of models predicting near-zero change, but also the result of two opposing changes that differ in sign, as seen in Figure 5.3. In water management, it is in the 'tails' of the full spectrum of model projections where the risk lies, and so failing to capture the extremes could be dangerous.

Potential exists for the range of model outcomes to vary so much that it could be construed as "noise". However, there is evidence that suggests a degree of consistency in some of the more salient changes generated by a collection of model outcomes. As an example, the trend in precipitation intervals as simulated by the IPCC AR4 models show, statistically and/or probabilistically speaking, agreement in the projection of the change in precipitation interval across latitudes, as climate warms. This implies that although one should not rely solely on a single model, each run could potentially contain important information that is more than merely 'noise'. Indeed, there are regions where a sign change is consistent amongst the climate models—but with a range that is important to consider explicitly for assessment of potential impacts.

A related issue is filtering or screening of GCM and SRES scenarios that are implausible, or at the very least, extremely unlikely. This is difficult—if not impossible—to unequivocally determine as there are no definitive criteria for determining whether a given climate change projection can or should be excluded. One approach in impact assessments is to consider all modeled projections as 'equally likely' at the outset of the assessment, and then to exclude in a secondary step those scenarios with minimal or limited impacts (and so to focus on those that could cause significant damage/consequence). Techniques are being developed for undertaking a full probabilistic analysis of scenarios to determine which are most applicable to each region, but these are not yet available for practical use.

Figure 5.3 Range of relative change from historical climate for different GCMs. Mean is shown in heavy line



Source: Giannini et. al., 2008 pg. 376, Fig. 6.

In this analysis, the full spread of model projections—including extremes—is captured by identifying dry, medium and wet climate scenarios, as defined by a change in the climate moisture index (CMI).[15] Model projections are not screened. Dry, middle and wet scenarios are identified, specific to each World Bank region (e.g., the driest scenario for LCR). A wet scenario means that the location experienced the smallest impact (or change in) CMI; a dry scenario, the largest impact; and a medium scenario, an impact in between the two extremes. The advantage of this approach is that it provides a representation of the full range of available scenarios in a 'manageable' way (further details are given below).

Analytical Framework

Key hydrologic variables for water planning and management

A number of hydrologic variables or indicators have been proposed in the literature to assist policy-makers and planners in decision-making. Themes emerging from this literature suggest a set of indicators that provide key information on the performance of water resource development projects in the near future, as well as in the distant future under the threat of climate

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[15] Note that *emissions scenarios* are distinct from *climate scenarios*, which are a plausible and often simplified representation of the future climate. Climate projections—the response of the climate system to emissions/concentration scenarios of greenhouse gasses and aerosols, or radiative forcing scenarios, based upon simulations by climate models—often serve as the raw material for constructing climate scenarios. A *climate change scenario* is the difference between a climate scenario and the current climate (Bates, et al, 2008).

change. The indicators chosen for this analysis provide information on *mean and extreme values of runoff, the storage requirements for reliable basin yield, groundwater recharge, and net irrigation water demand*.

SRES scenarios and GCMs

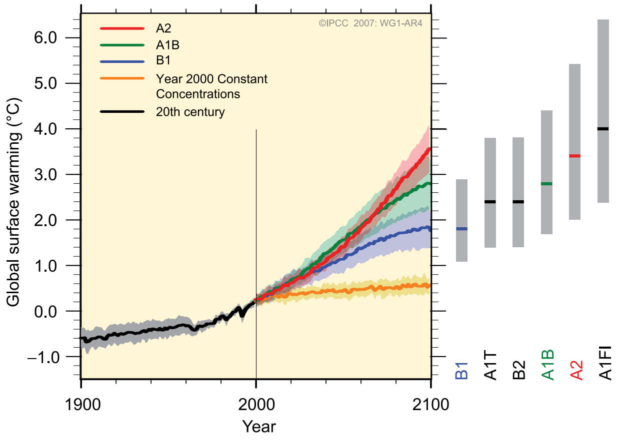
In this analysis, three SRES scenarios are used: B1, A1B, and A2. These scenarios are chosen because they are included in the marker scenarios identified by the IPCC and are in the middle range of SRES scenarios (Figure 5.4).[16]

There are 22 GCMs available via the IPCC 4th Assessment Report (AR4) to use in climate change analyses (Table 5.3). In this analysis all of the GCMs are evaluated to identify dry, medium and wet projections for each of the World Bank regions as discussed below.

Timeframe of analysis

Typical climate change analyses evaluate impacts anywhere from the 2030's to the 2100's. It is important to keep in mind the purpose of the analysis, i.e. near term planning or long range potential, to help guide which future decades are most important to evaluate for investment purposes. In this study the years 2030 and 2050 are used to evaluate the impacts of climate change on various hydrologic variables. These years are chosen for two reasons: (i) this is the relevant timeframe for current infrastructure planning and (ii) beyond 2050 uncertainties in projections increase dramatically. As shown in Figure 5.4, SRES scenarios are tightly bunched until 2050, at which time they start to diverge significantly.

Figure 5.4 Multi-model averages and assessed ranges for surface warming



Source: (IPCC 2007a, pg14, Figure SPM.5.) Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations.

The years 2030 and 2050 here represent decadal averages of monthly GCM output. In other words, when reporting changes in 2030 relative to historical climate, these are actually average changes from 2025 to 2035 relative to average historical climate. The same is true for the year 2050 (which represents the average from 2045 to 2055). Average monthly changes from the GCMs over the two separate decades are applied to historical monthly hydro-climatology from 1961 to 1990.

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[16] There are a total of 40 SRES scenarios, organized into four scenario families (A1, A2, B1 and B2). Marker scenarios represent a given scenario family, although they are not considered to be any more 'likely' than the other scenarios. These marker scenarios include A1B1, A2, B1, and B2, and two additional scenarios for the groups A1F1 and A1T.

Table 5.3 Available AR4 models, scenarios, and variables via IPCC

Models			
BCCR:	BCM2	MPIM:	ECHAM5
CCCMA:	CGCM3_1-T47	MRI:	CGCM2_3_2
CCCMA:	CGCM3_1-T63	NASA:	GISS-AOM
CNRM:	CM3	NASA:	GISS-EH
CSIRO:	MK3–5	NASA:	GISS-ER
CSIRO:	MK3–0	NCAR:	CCSM3
GFDL:	CM2	NCAR:	PCM
GFDL:	CM2_1	NIES:	MIROC3_2-HI
INM:	CM3	NIES:	MIROC3_2-MED
IPSL:	CM4	UKMO:	HADCM3
LASG:	FGOALS-G1_0	UKMO:	HADGEM1

Application of Tools to Dialogues at National, River Basin and Project Level Analysis

The level of analysis reflected in this report is designed for use at the Country Assistance Strategy discussions, national water strategy planning and identification of investment potential at river basin scale. Projections at the catchment level allow for analysis of inter-regional variation at the project planning scale. The general pattern is consistent with projections of runoff made directly from climate model runs. Here, specific indicators provide a deeper and more water specific insight regarding potential changes in the water availability and distribution for various uses and by various water infrastructure interventions. For each region, detailed information for each of these indicators is available at the 0.5 x 0.5 degree resolution, as well as aggregated to catchment level. It is planned that this information will be made available via a web-based interface.

Various hydrologic models can be used. The hydrologic model used for this study CLIRUN-II and its predecessors have been used extensively since 1992 specifically for climate change analysis. While there are a number of global hydrologic models that could be used, the results would not differ significantly since they solve the same set of governing equations. In this analysis the model was calibrated and validated using separate historical time series (see below).

Prior to using the methodology at project level it is important to consider that the analysis is based on natural flows and does not take into account specific basin development and structural interventions. These will have to be taken into consideration for detailed project design and risk assessment. The same is true for expected changes in land use and vegetation which impacts on the hydrology.

Project specific design will have to continue to be done taking into account historical, local scale surface data. In addition down-scaling from the local-scale surface weather may be carried out using the technique which the responsible task manager in each case deems to be most appropriate. Following such down-scaling it is possible to project hydrologic variables for the investment project in question. These may then be compared to projections based on historical data only; and a choice will have to be made with regard to how to take the climate change based projections into account. These calculations and the ensuing design will be carried out by the responsible engineer and will be based on the hydraulic model of his choice and the design parameters and safety factors which he deems appropriate in the light of the project and local regulations. A key value of the approach presented in this report is that it provides an easy to use database which can provide alternative scenarios as background for the project analysis to be undertaken.

Hydrologic drivers and data

Historical climate

The historical climate is taken from a database provided by the Climate Research Unit (CRU), University of East Anglia, Norwich, UK. The CRU 2.1 data set provides a time series of monthly precipitation data and the climate variables required to compute potential evapotranspiration from 1901 to 2002. These data, provided on a 0.5° longitude/latitude grid, represent the World Meteorological Organization's (WMO) standard reference "baseline" for climate change impact studies. The climate change scenarios (i.e. plausible descriptions of how things may change in future) are expressed as changes from this baseline. There are 67,420 grids (0.5° x 0.5°) over the global land area, excluding Antarctica.

Historical observed runoff

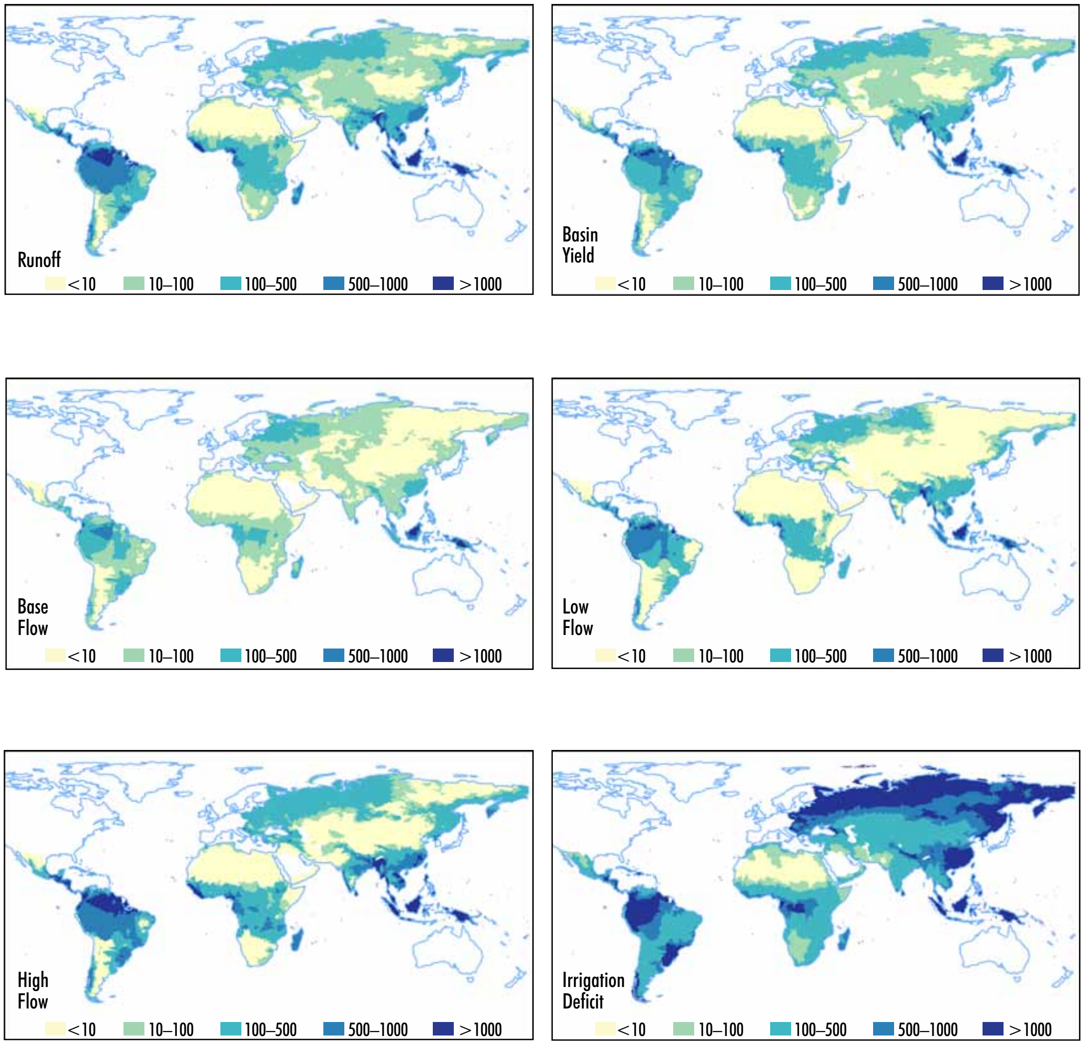
Long-term average monthly runoff has been developed by the University of New Hampshire for the WMO Global Runoff Data Centre. The "UNH-GRDC Composite Runoff Fields V1.0" data set is derived from observed discharge information, using a climate-driven water balance model. The dataset utilizes a gridded river network at 0.5°spatial resolution to represent the riverine flow pathways and to link the continental land mass to oceans through river channels. The data set provides 12 monthly mean values and a mean annual value of runoff for over 50,000 grids (0.5° x 0.5°) over the global land area excluding permanent ice cover such as much of Greenland and all of Antarctica.

Historical indicators as baseline for future water investment assessment

Assessment of the impacts of climate change on water investments requires historical time series of runoff and projection of hydrologic drivers. An observed global runoff time series does not exist. The disadvantage of the UNH-GRDC database (discussed above) is that the discharge is gauged, with all of the developments implicit in the measured data. For the purposes of this analysis, a new dataset based on natural flows has been developed. Using both the CRU Historical Climate Database and the UNH-GRDC Composite Runoff Fields V1.0 database as input to the global runoff model, CLIRUN-II (Strzepek, et al, 2008), 30-year monthly time series of runoff at the 50,000 plus grids of the UNH-GRDC data set was produced. The time series uses the monthly data from 1961 to 1990 to produce a historic or base condition against which the projections are compared. CLIRUN-II calibration is carried out using the CRU data from 1961–1980 and validation was performed using the CRU data from 1981–2002.

Indicators for assessment of specific water services and water management investment types are modeled as historic baselines (Figure 5.5). These indicators are: basin runoff, basin yield, 10%

Figure 5.5 Modeled historical baseline indicators at catchment scale for Bank regions (1961–1990). Units are in mm/yr.



and 90% exceedance probability flows, base flow, and irrigation demand deficit. A description of each indicator and their application in investment types is provided in the subsequent sections. The hydrologic indicators are aggregated to "level 4 catchment"[17] (approximately 2 x 2 degree resolution).

Figure 5.6 shows the modeled indicators for the Africa Region at the catchment scale. The entire data set reflecting the historical baseline conditions at the level 4 catchment scale is now available for all Bank regions upon request.

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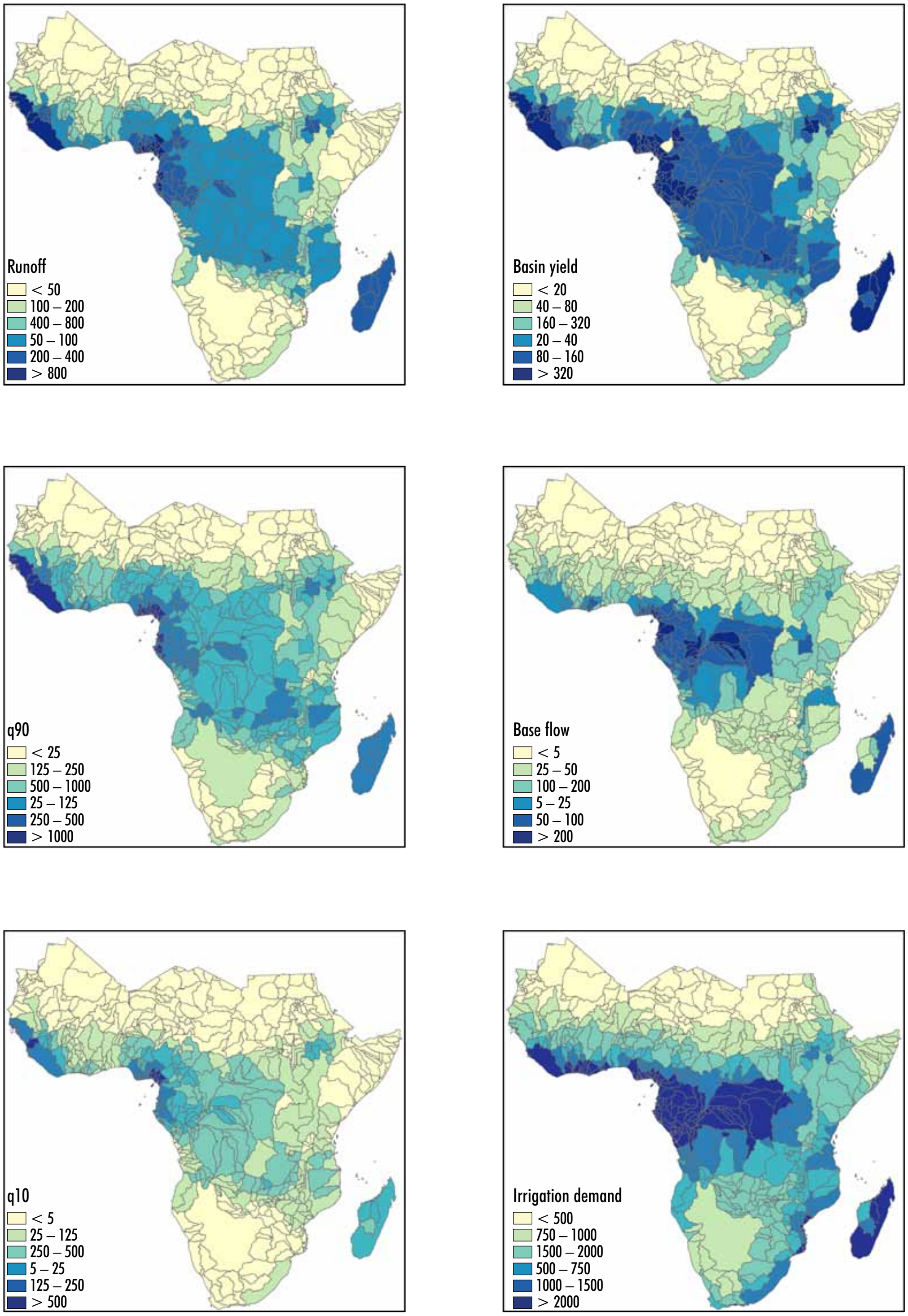
[17] The catchments are selected from the USGS Hydro 1K Drainage Basin Database. Level 4 catchment delineation has an approximate area of 2 x 2 degree. Level 4 was selected in order to gauge the hydrology results to the resolution level of GCM climate projections. This level also lends itself to water investments in river basins.

Figure 5.6 Modeled historical baseline indicators at catchment scale for Africa (1961–1990). Lines on the map delineate catchment boundaries. Units are in mm/yr.



Projections using Climate Moisture Index

The full spread of model results is captured by selecting the driest, the wettest, and middle climate projections. The historical model simulations and all 22 GCM projections for the three emissions scenarios are analyzed for 2030 and 2050. The driest, middle, and wettest projections are identified for each World Bank region (see Table 5.4 and Table 5.5). The projection categorization is defined by the Climate Moisture Index (CMI), which is an indicator of the aridity of a region. The CMI depends on average annual precipitation and average annual

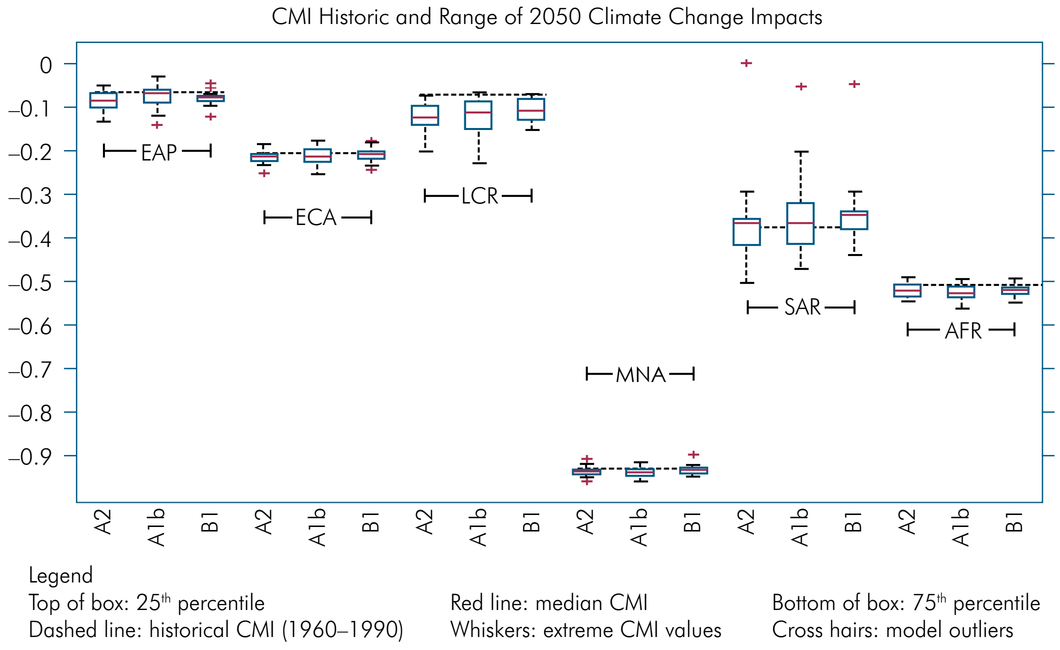
Table 5.4. GCM and associated base CMIs used for each scenario and regions EAP, ECA, and LCR

	EAP		**ECA**		**LCR**	
	–0.069		**–.205**		**–0.075**	
Base	**Model**	**CMI**	**Model**	**CMI**	**Model**	**CMI**
A2-Dry	csiro_mk3_5	–0.143	ipsl_cm4	–0.252	gfdl_cm2_0	–0.228
A2-Middle	mri_cgcm2_3_2a	–0.082	ukmo_hadcm3	–0.215	ukmo_hadcm3	–0.151
A2-Wet	cccma_cgcm3_1_t63	–0.033	giss_model_e_r	–0.177	cnrm_cm3	–0.068
A1B-Dry	csiro_mk3_5	–0.135	ipsl_cm4	–0.251	ukmo_hadgem1	–0.202
A1B-Midde	inmcm3_0	0.097	mpi_echam5	–0.212	mpi_echam5	–0.129
A1B-Wet	cccma_cgcm3_1	–0.054	cccma_cgcm3_1	–0.184	bccr_bcm2_0	–0.076
B1-Dry	csiro_mk3_5	–0.122	ipsl_cm4	–0.243	miroc3_2_hires	–0.153
B1-Middle	mri_cgcm2_3_2a	–0.084	mpi_echam5	–0.216	cccma_cgcm3_1	–0.11
B1-Wet	cccma_cgcm3_1_t63	–0.048	gfdl_cm2_1	–0.177	cnrm_cm3	–0.074

Table 5.5. GCM and associated base CMIs used for each scenario and regions MNA, SAR, and AFR

	MNA		**SAR**		**AFR**	
	–0.91		**–0.372**		**–0.5**	
Base	**Model**	**CMI**	**Model**	**CMI**	**Model**	**CMI**
A2-Dry	gfdl_cm2_1	–0.942	ipsl_cm4	–0.466	inmcm3_0	–0.552
A2-Middle	ukmo_hadgem1	–0.920	ukmo_hadcm3	–0.312	mpi_echam5	–0.519
A2-Wet	ncar_pcm1	–0.898	mri_cgcm2_3_2a	–0.055	ncar_ccsm3_0	–0.488
A1B-Dry	gfdl_cm2_1	–0.941	ipsl_cm4	–0.496	gfdl_cm2_1	–0.537
A1B-Midde	ukmo_hadcm3	–0.916	ukmo_hadgem1	–0.294	ukmo_hadgem1	–0.501
A1B-Wet	mpi_echam5	–0.891	mri_cgcm2_3_2a	–0.003	cnrm_cm3	–0.484
B1-Dry	gfdl_cm2_1	–0.930	csiro_mk3_5	–0.433	ipsl_cm4	–0.539
B1-Middle	inmcm3_0	–0.907	inmcm3_0	–0.291	miroc3_2_medres	–0.517
B1-Wet	mpi_echam5	–0.882	mri_cgcm2_3_2a	–0.051	cnrm_cm3	–0.486

Figure 5.7 Climate Moisture Index range for each climate scenario and each Bank region


CMI Historic and Range of 2050 Climate Change Impacts

potential evapotranspiration (PET).[18] If PET is greater than precipitation, the climate is considered to be dry whereas if precipitation is greater than PET, the climate is moist. Calculated as CMI = (P/PET)–1 {when PET>P} and CMI = 1–(PET/P) {when P>PET}, a CMI of –1 is very arid and a CMI of +1 is very humid. CMI is dimensionless.

Figure 5.7 shows the projected range of CMI for each scenario and each region of the World Bank for 2050. The red line represents the median CMI, and the top of the box represents the 25th percentile while the bottom of the box represents the 75th percentile. The whiskers show the extremes and the cross-hairs show the model outliers. The dashed lines represent the historical CMI (averaged from 1960–1990). For example, in the LCR region, there is a 75% chance of drying with all 3 scenarios. The CMI for the SAR region has the largest spread because of the way the different GCMs model the monsoons. In the MNA region, there is little variation because the area is so dry.

In this analysis the CMI is calculated over land masses only. Many climate change analyses discuss GCM projections over land and sea, but for hydrologic impacts, the interest in CMI is over land only. Moreover, note that the land-based CMI in the box and whiskers plot are all negative. Figure 5.8 shows the projected range of CMI for Bank regions, non-Bank regions and the globe. Note that the land-based CMI projections for the Bank regions are more negative than non-Bank regions (e.g., OECD). However, the relative aridity (compared with the historical) for both Bank and non-Bank regions remains the same.

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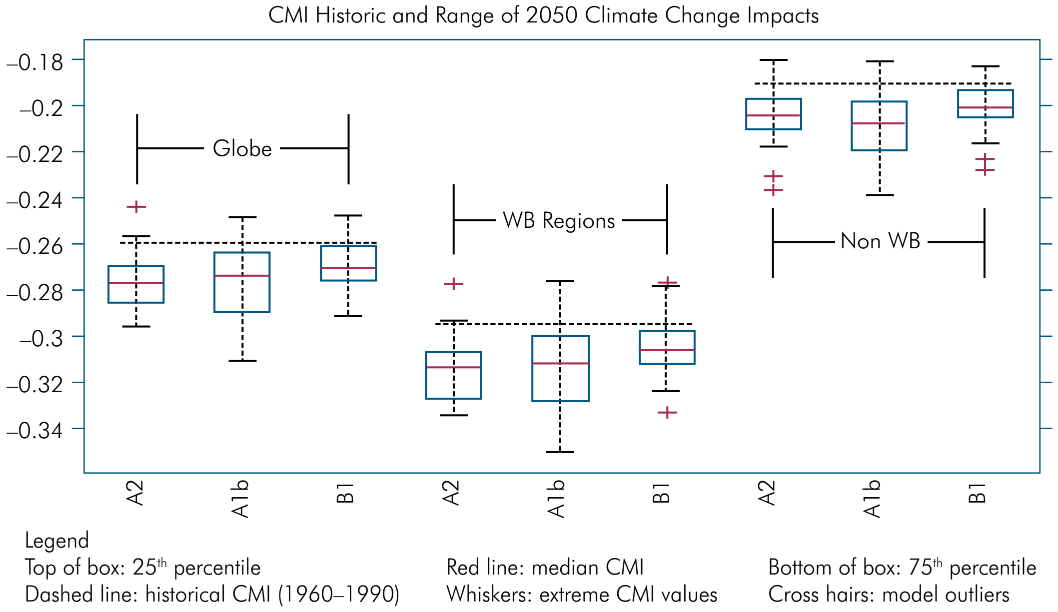
18 Average annual PET is a parameter that reflects the amount of water lost via evaporation or transpiration (water consumed by vegetation) during a typical year for a given area if sufficient water were available at all times. Average annual evapotranspiration (ET) is a measure of the amount of water lost to the atmosphere from the surface of soils and plants through the combined processes of evaporation and transpiration during the year (measured in mm/yr). ET, which is both connected to and limited by the physical environment, is a measure that quantifies the available water in a region. Potential evapotranspiration is a calculated parameter that represents the maximum rate of ET possible for an area completely covered by vegetation with adequate moisture available at all times. PET is dependent on several variables including temperature, humidity, solar radiation and wind velocity. If ample water is available, ET should be equal to PET.

Figure 5.8 Climate Moisture Index range comparison of Bank and non-Bank regions



Runoff projections

A variety of approaches/models exist for generating runoff projections.[19] In this analysis, GCM output is used as input into the hydrologic model CLIRUN-II (Strzepek, et al, 2008). This model was developed specifically to assess the impact of climate change on runoff and to address extreme events at the annual level by modeling low and high flows. This analysis advances an earlier and much referenced effort by Milly, et al (2005). CLIRUN-II is an "offline" hydrologic model designed for application in water resource projects. Milly uses runoff estimates derived directly from approximately 2.5° x 2.5° GCM precipitation projections and reports annual runoff at 5° x 5° resolution with some degree of confidence. In this analysis, runoff is projected at a monthly time scale at a resolution 0.5° x 0.5°,using CLIRUN-II. The results are then aggregated to about 2° x 2° for a higher level of confidence.

Table 5.6 provides the projected percentage change in runoff at catchment scale for 2030 and 2050 for all Bank regions. The results are reported for three SRES scenarios and for the identified dry, medium (middle) and wet projections. Projected change in runoff for 2030 is mapped for all Bank regions and presented in Figure 5.9. An example of the regional distribution of change in runoff for the Africa Region is provided in Figure 5.10.

Basin yield projections

Annual runoff provides information on potential water resource availability, but not its accessibility which is a function of reservoir storage. Basin yield—which is directly related to reservoir storage—is a measure of the firm yield and reliability of water supply and is estimated with the aid of a 'storage yield curve'. A storage yield curve is an estimated time series of annual

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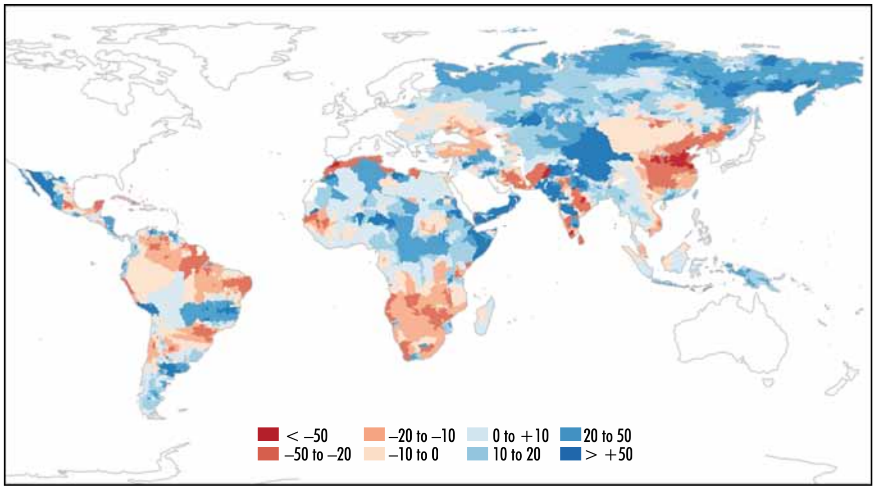
[19] The various approaches are discussed in detail in the companion report on the science of water and climate change.

or monthly flows in a basin and is used to provide information on (i) the storage needed to provide a specific amount of reliable yield and (ii) for any given storage, the reliable yield that can be expected. Difference between K and K′ is storage needed to compensate for basin yield loss between

Table 5.6 Summary changes in runoff projections for Bank regions

SRES Scenario	Year	Projection	AFR	EAP	ECA	LCR	MNA	SAR
A2	2030	Dry	–5%	–13%	5%	–16%	–17%	–7%
		Medium	6%	–4%	9%	–3%	–17%	26%
		Wet	30%	7%	13%	15%	24%	31%
	2050	Dry	–13%	–11%	8%	–31%	–50%	–52%
		Medium	14%	3%	18%	–9%	–5%	20%
		Wet	31%	11%	18%	7%	31%	39%
A1B	2030	Dry	–5%	7%	9%	–9%	–25%	18%
		Medium	3%	5%	13%	–5%	12%	18%
		Wet	–1%	11%	10%	9%	15%	43%
	2050	Dry	–20%	–12%	14%	–25%	–46%	24%
		Medium	0%	–2%	21%	–16%	–16%	24%
		Wet	6%	21%	19%	7%	20%	37%
B1	2030	Dry	–1%	–8%	6%	–13%	–15%	–20%
		Medium	–9%	2%	11%	–11%	12%	–5%
		Wet	10%	14%	16%	11%	18%	36%
	2050	Dry	–8%	–8%	5%	–9%	–30%	–14%
		Medium	–12%	–1%	14%	–9%	19%	38%
		Wet	23%	15%	19%	9%	49%	33%

Figure 5.9 Projected percent change in runoff for 2030



2005 and 2050 due to climate change. The maximum yield of the storage yield curve is generally equivalent to the average annual runoff (ignoring evaporation) and the minimum yield is the lowest flow in the time series. Climate change has the potential to impact not only the average annual runoff in a basin, but also the variability and the shape of the storage yield curve (Figure 5.11).

Table 5.7 shows the percentage change in basin yield at a catchment level in the years 2030 and 2050. The results are reported for three SRES scenarios and for the identified dry, medium (middle) and wet projections. Projected change in basin yield for 2030 is mapped for all Bank regions and

Figure 5.10 Projected percent change in runoff for 2030 at catchment level – Africa Region. Catchment boundaries are not delineated

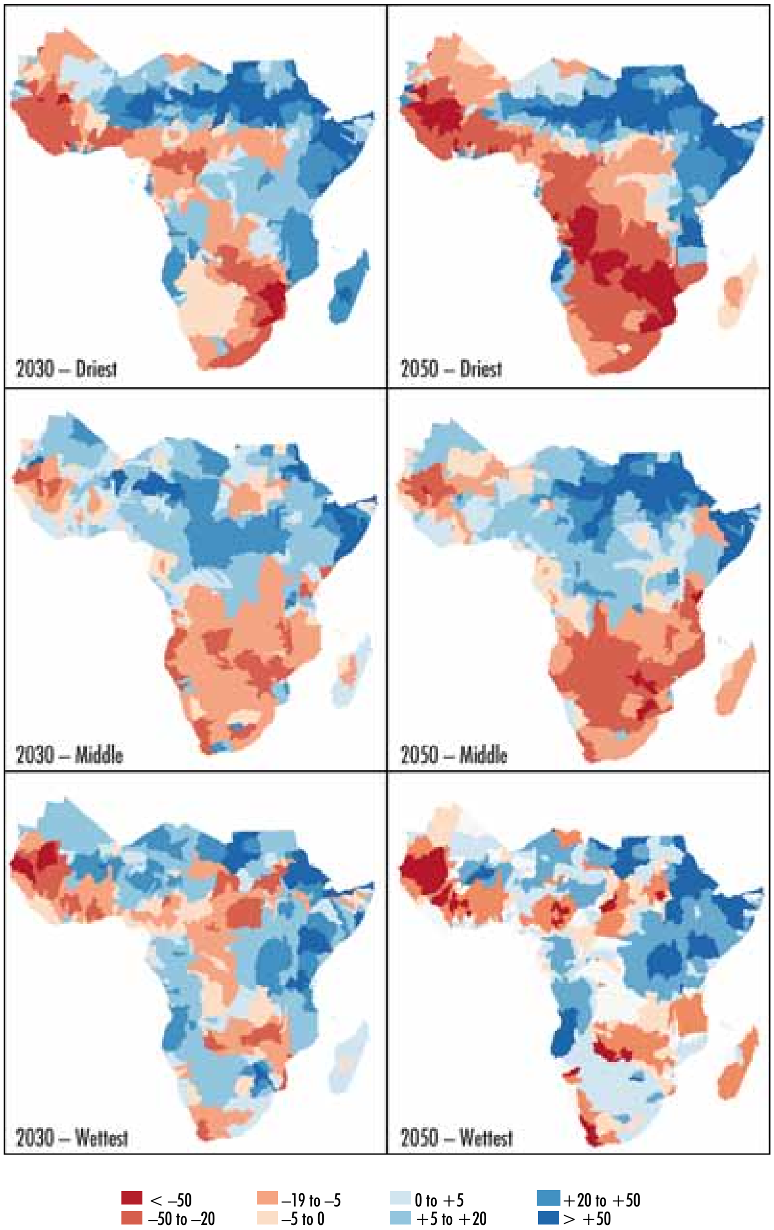


Table 5.7 Summary changes in basin yield projections for Bank regions

SRES Scenario	Year	Projection	AFR	EAP	ECA	LCR	MNA	SAR
A2	2030	Dry	21%	42%	–2%	44%	61%	40%
		Medium	9%	14%	–9%	17%	60%	–14%
		Wet	–22%	–7%	–13%	–10%	–4%	–22%
	2050	Dry	38%	42%	–3%	74%	136%	53%
		Medium	–2%	0%	–14%	39%	24%	–5%
		Wet	–19%	–13%	–18%	5%	4%	–29%
A1B	2030	Dry	26%	–4%	–9%	29%	85%	–19%
		Medium	3%	–2%	–16%	26%	–17%	–19%
		Wet	7%	–12%	–7%	–1%	–11%	–29%
	2050	Dry	53%	49%	–12%	57%	141%	–18%
		Medium	12%	10%	–24%	53%	55%	–18%
		Wet	–4%	–25%	–21%	6%	–19%	–32%
B1	2030	Dry	8%	35%	–2%	38%	46%	45%
		Medium	27%	1%	–15%	35%	13%	27%
		Wet	–5%	–17%	–15%	–6%	–7%	–26%
	2050	Dry	30%	26%	4%	27%	103%	30%
		Medium	37%	7%	–16%	30%	26%	–31%
		Wet	–14%	–20%	–21%	–5%	–29%	–28%

presented in Figure 5.12. An example of the regional distribution of change in runoff for the Africa Region is provided in Figure 5.13.

Extreme events projections

Annual runoff and basin yield provide information on average conditions, more is needed. It is in the 'extremes' where the risks of climate change to water investments and planning lie. This assessment is one of the first attempts to develop indicators—for floods and droughts—based on time-series rather than long-term averages. As compared to 'mean' value indicators, indicators of extreme events carry more uncertainty due to the limited data at the tail

Figure 5.11 Impact of climate change on reservoir yield and adaptations

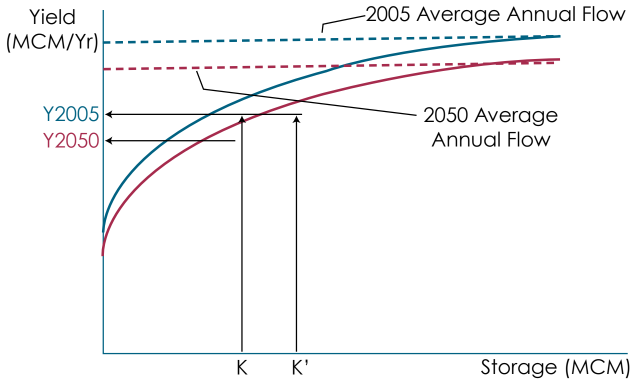


Figure 5.12 Projected percent change in basin yield for 2030

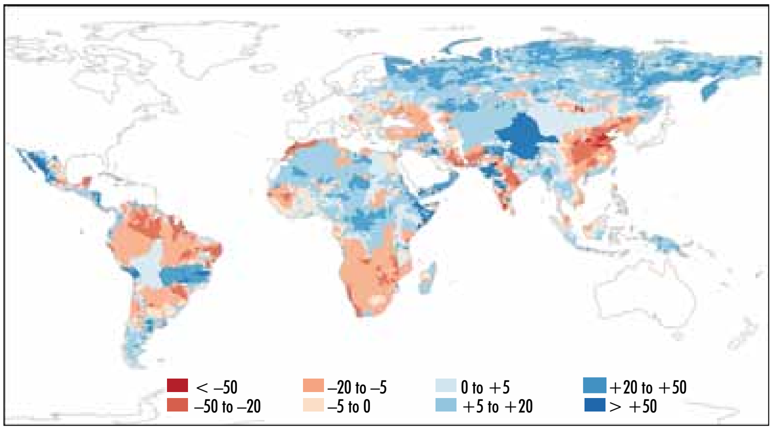
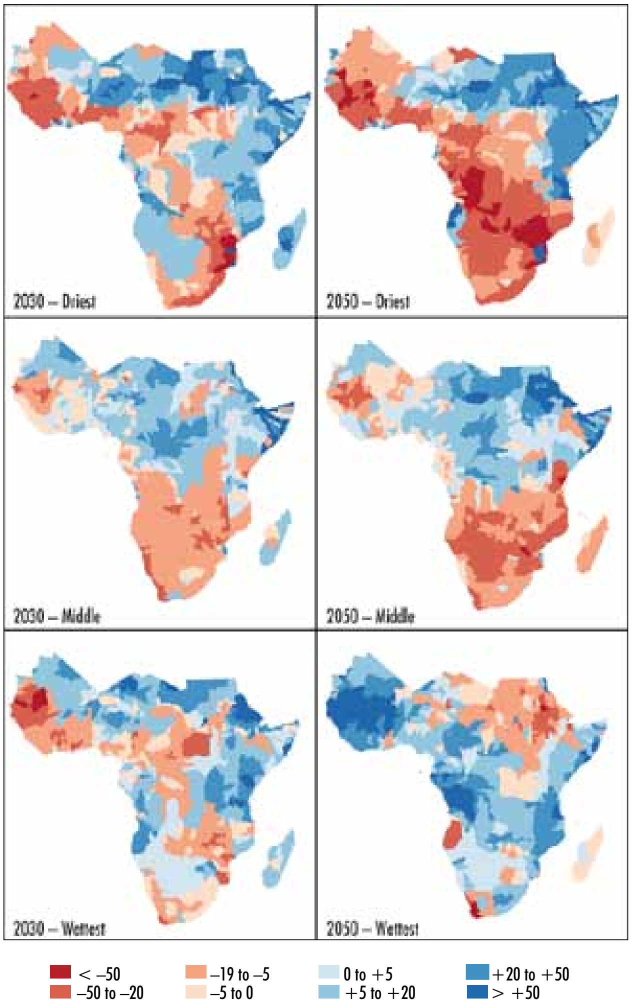


Figure 5.13 Projected percent change in basin yield for 2030 at catchment level – Africa Region. Catchment boundaries are not delineated



of the probability distribution. However, it is useful to have some indication of extreme events, even while bearing this additional uncertainty in mind.

Drought and flood indicators are estimated based on flow frequency analysis.

- Drought indicator: This indicator is taken as the flow that is exceeded 90% of the time (q90), which means there is a 10% chance in each time period of a flow lower than this. A decrease in q90 means that the likelihood of low flows and droughts will increase.
- Flood indicator: This indicator is taken as the flow that is exceeded 10% of the time (q10), which means there is a 90% chance in each time period of a flow lower than this. An increase in q10 means that the likelihood of high flows and floods will increase.

The relative changes in the q90 and q10 from the historical values will provide an "indication" of the projected changes in droughts and floods.

Table 5.8 and Table 5.9 show the percentage change in q90 and q10, respectively, at a catchment level for 2030 and 2050. The results are reported for three SRES scenarios and for the identified dry, medium (middle) and wet projections. Projected changes in drought and flood for 2030 are mapped for all Bank regions and presented in Figure 5.14 and Figure 5.15. An example of the regional distribution of change in floods and droughts for the Africa Region is provided in Figure 5.16 and Figure 5.17.

Table 5.8 Summary changes in low flow projections for Bank regions

SRES Scenario	Year	Projection	AFR	EAP	ECA	LCR	MNA	SAR
A2	2030	Dry	–4%	–14%	7%	–18%	–19%	–5%
		Medium	6%	–4%	10%	–2%	–18%	31%
		Wet	37%	8%	14%	19%	18%	31%
	2050	Dry	–15%	–11%	10%	–35%	–52%	–55%
		Medium	19%	3%	21%	–11%	–8%	21%
		Wet	40%	13%	19%	9%	17%	41%
A1B	2030	Dry	–5%	7%	11%	–11%	–29%	20%
		Medium	3%	5%	15%	–5%	9%	20%
		Wet	–1%	12%	10%	9%	13%	47%
	2050	Dry	–23%	–13%	18%	–32%	–50%	25%
		Medium	0%	–2%	23%	–18%	–24%	25%
		Wet	7%	21%	19%	8%	3%	40%
B1	2030	Dry	0%	–9%	9%	–17%	–19%	–22%
		Medium	–12%	2%	13%	–15%	9%	–3%
		Wet	13%	14%	17%	10%	12%	37%
	2050	Dry	–8%	–9%	7%	–13%	–34%	–17%
		Medium	–14%	–1%	17%	–13%	8%	48%
		Wet	30%	14%	20%	9%	37%	37%

Table 5.9 Summary changes in high flow projections for Bank regions

SRES Scenario	Year	Projection	AFR	EAP	ECA	LCR	MNA	SAR
A2	2030	Dry	–4%	–13%	5%	–16%	–15%	–8%
		Medium	5%	–3%	8%	–2%	–16%	23%
		Wet	27%	7%	13%	14%	25%	32%
	2050	Dry	–11%	–10%	7%	–28%	–48%	–50%
		Medium	13%	3%	17%	–9%	–4%	21%
		Wet	27%	11%	17%	7%	36%	39%
A1B	2030	Dry	–4%	7%	8%	–8%	–24%	18%
		Medium	3%	5%	13%	–4%	10%	18%
		Wet	–1%	10%	10%	9%	13%	43%
	2050	Dry	–18%	–12%	12%	–21%	–43%	24%
		Medium	1%	–2%	20%	–14%	–13%	24%
		Wet	6%	20%	19%	7%	27%	35%
B1	2030	Dry	–1%	–8%	6%	–11%	–13%	–18%
		Medium	–7%	2%	10%	–9%	12%	–5%
		Wet	9%	13%	17%	11%	22%	36%
	2050	Dry	–7%	–8%	4%	–7%	–26%	–12%
		Medium	–10%	–1%	13%	–7%	20%	34%
		Wet	20%	15%	19%	8%	52%	32%

Figure 5.14 Projected percent change in low flows (drought) for 2030

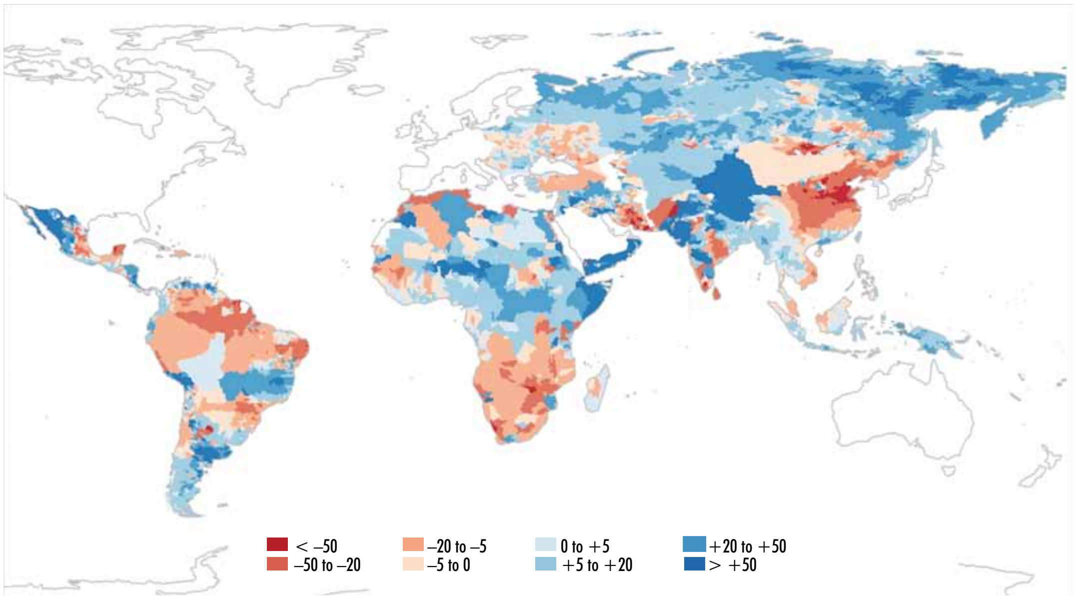


Figure 5.15 Projected percent change in high flows (floods) for 2030

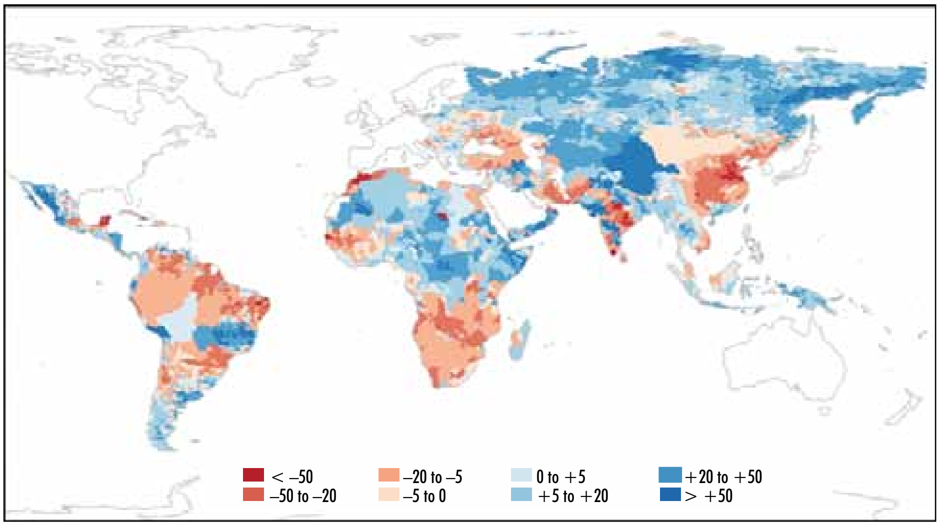


Figure 5.16 Projected percent change in low flows (drought) for 2030 at catchment level – Africa Region. Catchment boundaries are not delineated

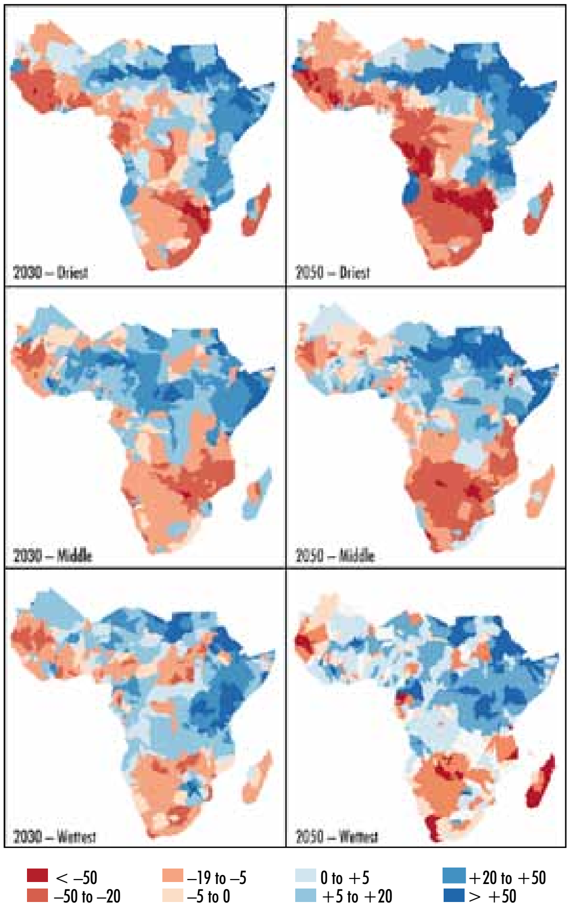
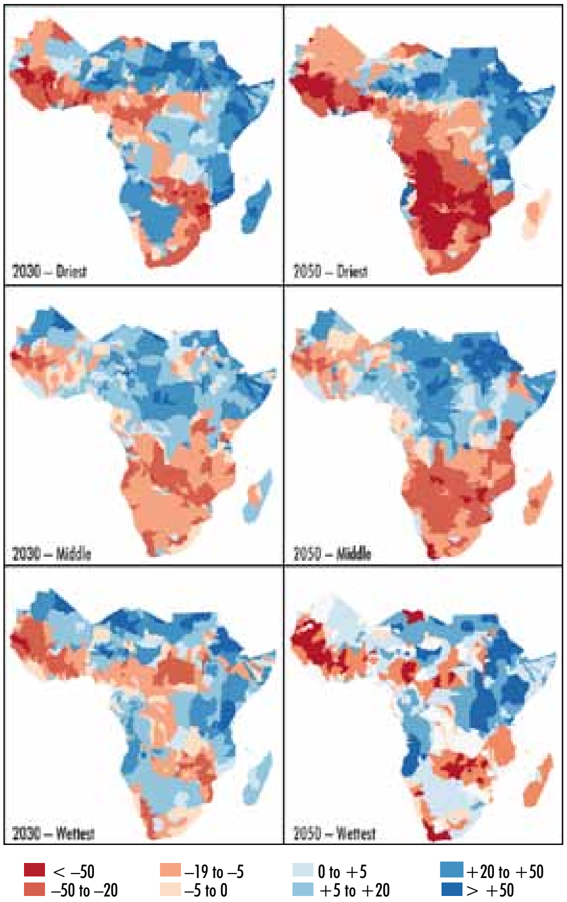


Figure 5.17 Projected percent change in high flows (floods) for 2030 at catchment level – Africa Region. Catchment boundaries are not delineated



Base flow projections

Much of water resources development, particularly rural water supply and small scale irrigation, is dependent on groundwater resources. It is important to provide an indicator of the impact of climate change on local groundwater resources. Modeling of the global groundwater system is highly complex and well beyond the scope of this analysis. However, a screening level proxy indicator—base flow—can provide important information, and provide some indication of the water available in the basin (deep groundwater excluded) for basin management interventions and conjunctive water use. For each catchment, the 30-year monthly time series is analyzed for estimation of the base flow as the contribution of shallow groundwater to the runoff.

Table 5.10 shows the percentage change in base flow at catchment level for 2030 and 2050. The results are reported for three SRES scenarios and for the identified dry, medium (middle) and wet projections. Projected change in base flow for 2030 is mapped for all Bank regions and presented in Figure 5.18. An example of the regional distribution of change in base flow for the Africa Region is provided in Figure 5.19.

Table 5.10 Summary changes in base flow projections for Bank regions

SRES Scenario	Year	Projection	AFR	EAP	ECA	LCR	MNA	SAR
A2	2030	Dry	–14%	–32%	21%	–24%	–7%	–14%
		Medium	–7%	–13%	12%	–7%	–19%	33%
		Wet	27%	6%	19%	17%	4%	32%
	2050	Dry	–12%	–30%	26%	–37%	–51%	–44%
		Medium	–8%	–6%	33%	–18%	–9%	25%
		Wet	12%	10%	33%	21%	58%	35%
A1B	2030	Dry	–9%	2%	20%	–11%	–30%	27%
		Medium	5%	2%	24%	–10%	4%	27%
		Wet	0%	9%	23%	16%	5%	47%
	2050	Dry	–17%	–34%	33%	–33%	–57%	27%
		Medium	–3%	–12%	40%	–19%	–17%	27%
		Wet	13%	35%	29%	8%	17%	37%
B1	2030	Dry	–4%	–19%	19%	–14%	–18%	–10%
		Medium	–10%	–2%	6%	–6%	–13%	–16%
		Wet	8%	23%	20%	21%	15%	28%
	2050	Dry	–14%	–21%	18%	–14%	–39%	–5%
		Medium	–13%	–13%	33%	–2%	12%	24%
		Wet	10%	21%	23%	2%	87%	29%

Figure 5.18 Projected percent change in base flow for 2030

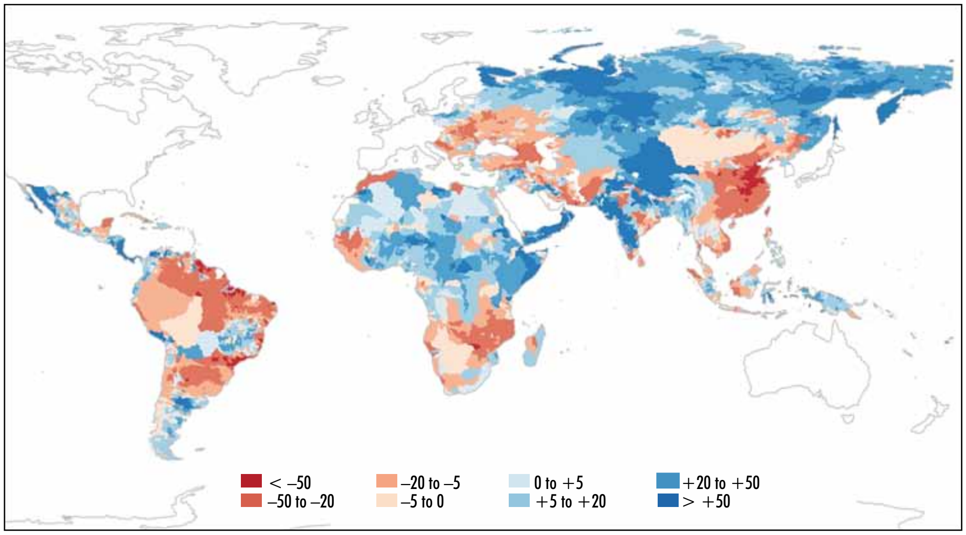
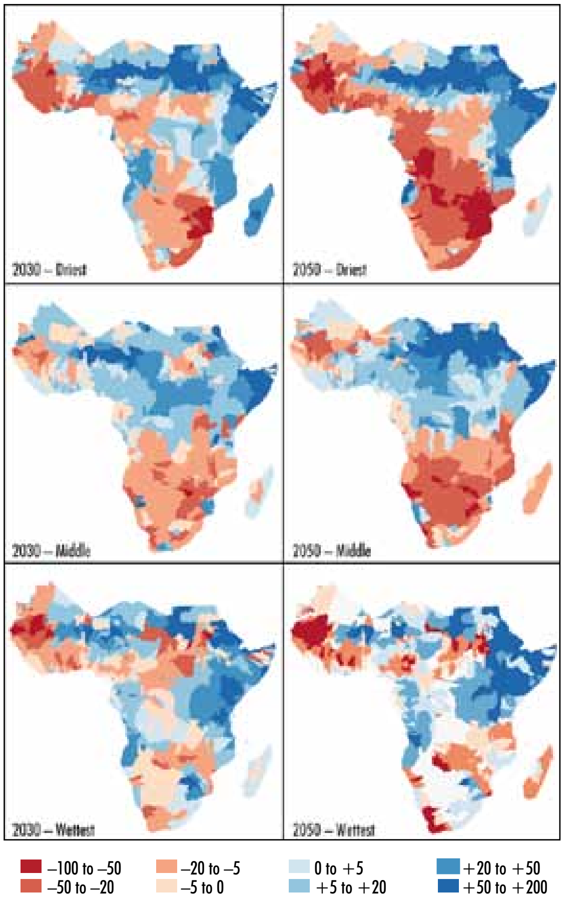


Figure 5.19 Projected percent change in base flow for 2030 at catchment level – Africa Region. Catchment boundaries are not delineated



Net irrigation demand projections

Irrigation is a major user of water and could be significantly impacted by climate change. Detailed crop modeling at the global grid scale is well beyond the scope of this analysis, but 'simpler' methods can provide important information on net irrigation demand at a broader scale. Water Deficit Index (WDI) can be used as an indicator of irrigation performance. The WDI has recently been developed for the reference crop, grass, as a generic index for quantifying crop water stress for various crops. This simple method has been employed for climate change analyses at local and regional levels.

The Water Deficit Index (WDI) is an estimate of the difference between precipitation and crop water requirements, on a monthly time scale:

$$\text{WDI} = \sum (\text{CWR} - \text{Precip})_t \text{ if } \text{CWR}_t - \text{Precip}_t > 0 \text{ else } 0$$

where,

$\text{CWR} = K_c(t) * \text{PET}(t)$
K_c = crop factor (crop per drop)
PET = Potential Evapotranspiration

WDI assumes a reference perennial grass crop factor, $K_{c,}$ which has a value of one. The Modified Hargreaves methodology is used for calculating PET. PET data are consistent with what is used in the runoff and basin yield analysis (refer above discussion) and CLIRUN-II model. The calculation of the CWR is performed at the gridded scale and aggregated to the catchment and regional levels.

Table 5.11 shows the percentage change in water deficit index at catchment level for 2030 and 2050. The results are reported for three SRES scenarios and for the identified dry, medium (middle) and wet projections. Projected change in water deficit index for 2030 is mapped for all Bank regions and presented in Figure 5.20. An example of the regional distribution of change in water deficit index for the Africa Region is provided in Figure 5.21.

Table 5.11 Summary changes in water deficit index projections for Bank regions

SRES Scenario	Year	Projection	AFR	EAP	ECA	LCR	MNA	SAR
A2	2030	Dry	0%	122%	10%	40%	–5%	9%
		Medium	–1%	91%	–15%	30%	–1%	–6%
		Wet	–10%	70%	–18%	12%	–4%	–10%
	2050	Dry	–2%	127%	17%	69%	6%	26%
		Medium	4%	87%	–16%	37%	0%	–3%
		Wet	5%	74%	–16%	21%	–12%	–5%
A1B	2030	Dry	13%	106%	30%	59%	14%	33%
		Medium	13%	97%	19%	59%	7%	4%
		Wet	10%	90%	19%	25%	7%	3%
	2050	Dry	29%	141%	44%	87%	23%	33%
		Medium	18%	114%	28%	64%	15%	4%
		Wet	5%	65%	19%	39%	11%	11%
B1	2030	Dry	15%	125%	35%	41%	10%	23%
		Medium	16%	104%	9%	23%	10%	22%
		Wet	9%	71%	6%	13%	8%	5%
	2050	Dry	20%	132%	44%	48%	14%	17%
		Medium	18%	117%	25%	22%	8%	12%
		Wet	16%	67%	5%	44%	–5%	10%

Figure 5.20 Projected percent change in water deficit index for 2030

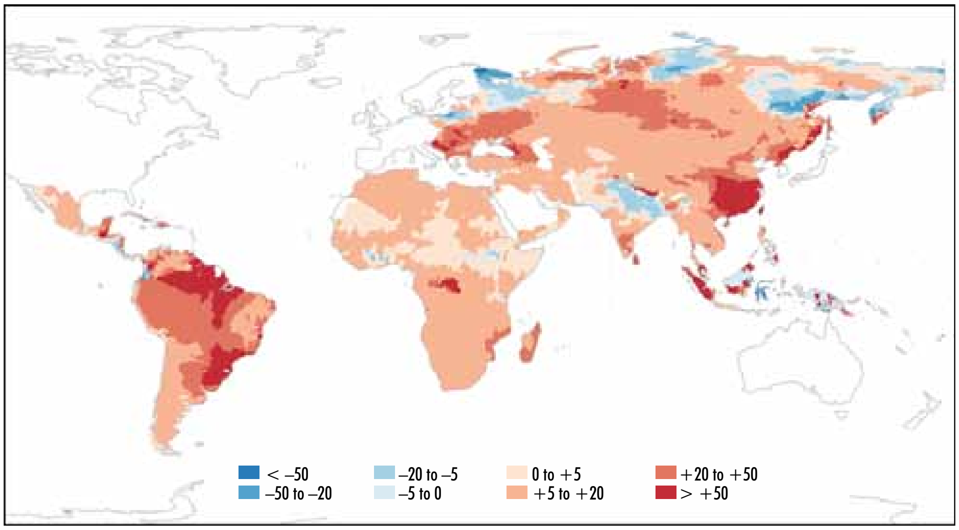
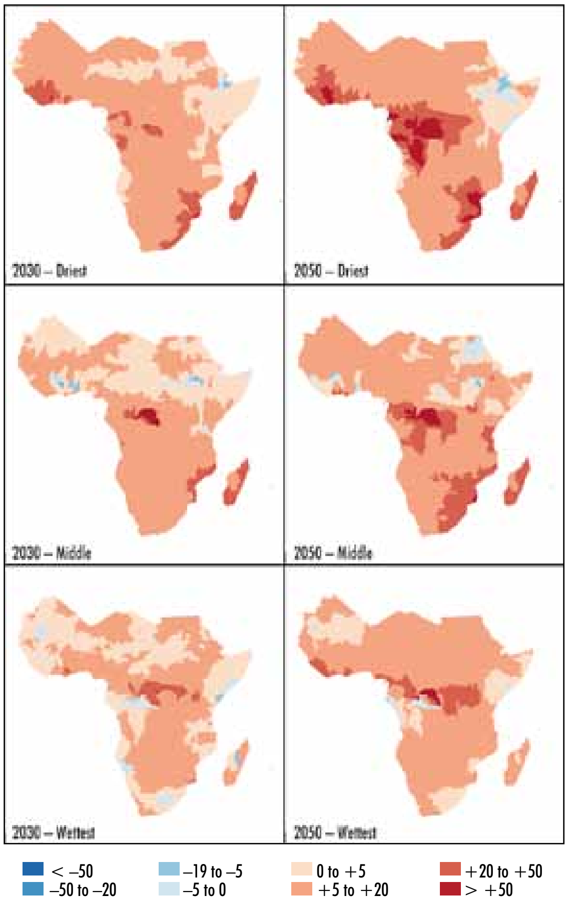


Figure 5.21 Projected percent change in water deficit index for 2030 at catchment level – Africa Region. Catchment boundaries are not delineated



CHAPTER 6:
CLIMATE CHANGE AND THE WORLD BANK WATER PORTFOLIO

Introduction

Climate change poses risk to World Bank investments in the water sector. In order to understand the magnitude of water challenges and the exposure of Bank's investments to climate change, a detailed analysis of the water portfolio was conducted. This chapter attempts to review Bank's investments in the water sector over the period fiscal year 2006–2010 and establish potential linkages to climate variability and change. More specifically, the objective of this chapter is to assess the exposure of Bank's water investment to current hydrologic variability and future climate change. To this end, this chapter covers the following:

- Assess the World Bank's current portfolio and pipeline in the water sector, identifying the financing directed to the different water systems (services and resources).
- Analyze the extent in which Bank projects adopt measures with respect to climate variability or climate change at the project design level. The focus is on adaptation, but projects with mitigation measures were also identified.
- Identify the exposure of Bank's investments to the hydrologic aspect of climate change.

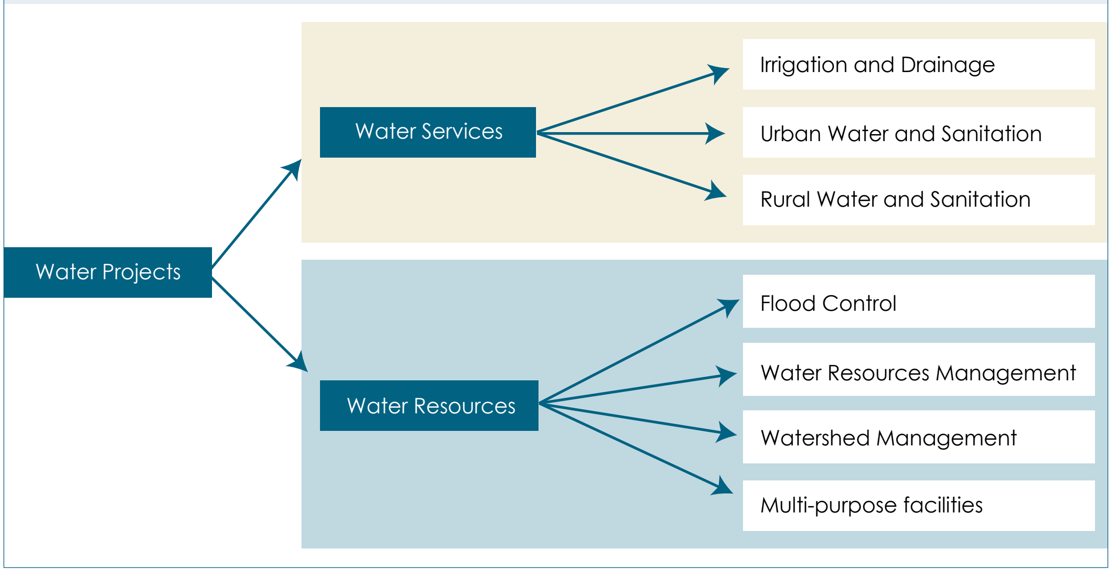
Framework for analysis

Classification of water systems used for the 2003 Water Resources Sector Strategy is adopted here. This allows the project lending information to be disaggregated into different water systems. A single project may have one or more water systems assigned to it. This level of detail is not available in the Bank's institutional database, thus the reason for this comprehensive review. By definition, a "system" includes all elements and components that make it perform its intended function under a defined set of conditions. This includes hardware, software, institutions, and more. For the purposes of this review and clarity, the definitions provided here are divided into the physical (infrastructure) and institutions (all other aspects) parts. This will allow addressing the climate impact and vulnerability for each aspect separately while recognizing that the infrastructure and institutional aspects of a system are inseparable.

The investments in the water sector are divided into two major categories/systems: those that help deliver services and those that manage the resource. Figure 6.1 shows the classification of water systems used in this review. The reason for this categorization is that impact of climate change on services delivery systems is expected to be different from systems designed for management of the resources. The same is true for adaptation options that may be selected. Naturally, the exposure to climate change and the need for adaptation are more pronounced the longer the lifetime of the infrastructure.

The Project Appraisal Document (PAD) was reviewed in detail for each project in order to identify the different water systems and allocate the costs to each system. When the PAD was not available (which was the case in some pipeline projects), the Project Information Document (PID) or the Integrated Safeguard Data Sheet was used for cost allocation. In order to ensure consistency with the total lending of the sector, the total lending allocated to each water system, with exception of multi-purpose facilities, did not exceed that reported by the Bank's institutional database. Since multi-purpose facilities (e.g. dams, hydropower) are not captured

Figure 6.1 Classification of water systems



automatically in the Bank's institutional database, additional lending was allocated to the total water lending. For projects in the pipeline with limited information, the project's file (in the Operations Portal) was examined to obtain more information about the project. In some cases, the project task manager was contacted for additional information.

The global water challenges bring increasing demands for World Bank engagement in developing countries. In 2003, the Board of Directors of the Bank approved a Water Resources Sector Strategy which delivered several key messages regarding the sector. As part of this Strategy, an assessment of the World Bank water portfolio was conducted to understand the magnitude of Bank investments in the water sector. The assessment showed that the composition and value of water investments in the Bank are very diverse with wide regional variations in the patterns of lending for water-related projects. Following the first assessment of the Bank's water portfolio, a similar review of the Bank's investments in water over the period FY06–10 is made with focus on potential linkages to climate variability and change. The objective of this assessment is to determine the extent to which the Bank's water portfolio is exposed to hydrologic variability and change, and whether potential actions to mitigate the negative impacts have been considered in project design.

Content of the water portfolio

The composition of the World Bank investments in water is very diverse with wide regional variations in the lending for water projects. For the FY06–08 period, water investments were committed in 83 countries across the six regions of the Bank (Figure 6.2 and Figure 6.3).

The World Bank's water portfolio selected for this review consists of 191 active projects approved in FY06–08 with total net commitments of $8.8 billion. For approvals in FY06–08, the water lending represents 11% of the total World Bank's investments (Figure 6.4). The regions that invested the most in water relative to their total WB regional investment are MNA (14%) and SAR (14%) and the region that invested the least is LCR (8%). On a yearly basis, the share of water

Figure 6.2 Location of World Bank water projects for FY06–08 (active) and FY09–10 (pipeline)

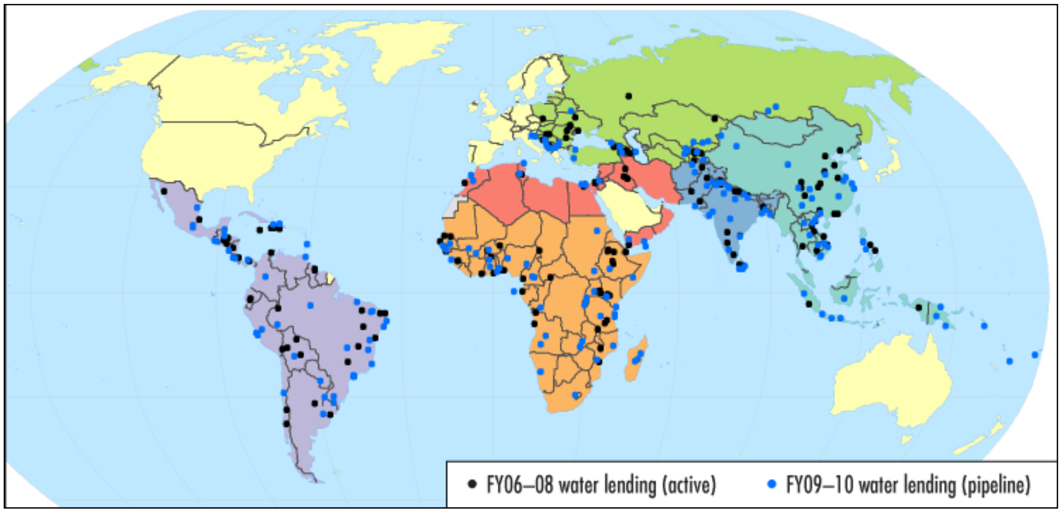
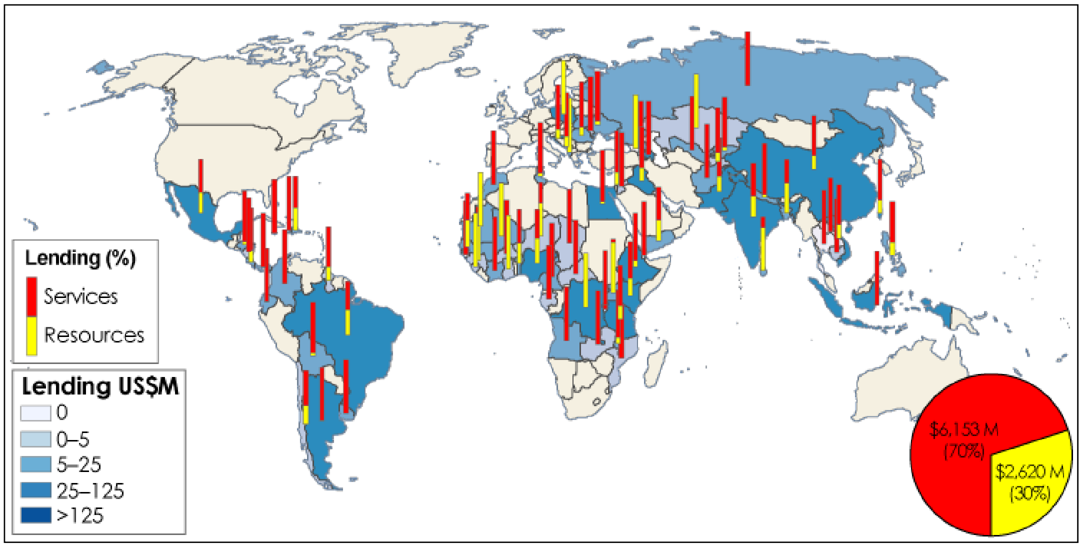


Figure 6.3 World Bank water lending volume (shading) and class (bar) for FY06–08



lending relative to the overall World Bank's investments has increased from 8% in FY06 to 12% in FY08. Yearly average water lending for the FY06–08 period amounts to $2.9 billion. A pipeline of projects with expected approvals in FY09–10 consists of 220 projects corresponding to a volume of US$11.3 billion[20] (Figure 6.5).

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[20] Pipeline results should be considered with caution because of the changes in approval dates, commitment amounts, etc, during the preparation phase of the project.

AFR region has led the lending in water with a total of $2 billion for the past three fiscal years (24% of Bank's overall water investments) consisting of 52 active projects. The second largest share of water commitments is in SAR (23%) corresponding to 28 projects, followed by EAP (19%), ECA (14%) and LCR (13%). MNA region accounts for the smallest share both in terms of investments (7%) and number of projects (8%) as shown in Figure 6.6.

Figure 6.4 Water lending as a share of overall regional lending in the FY06–08

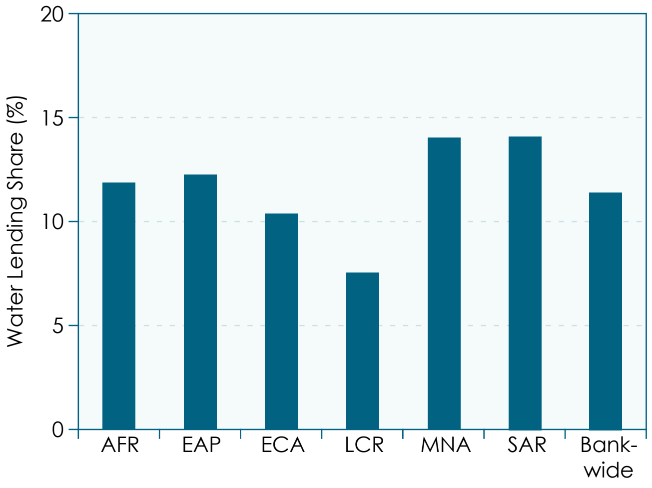
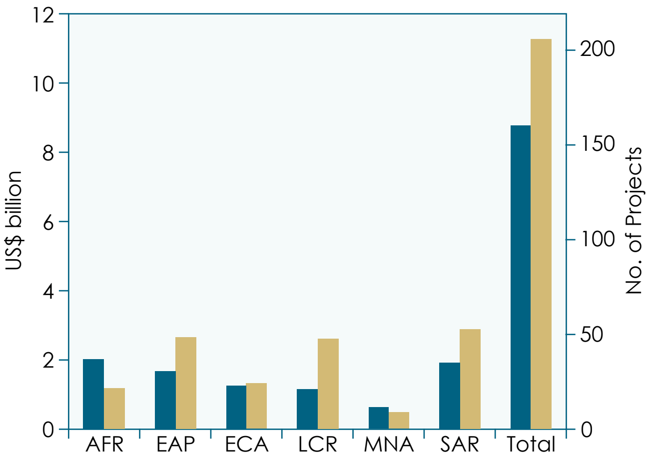


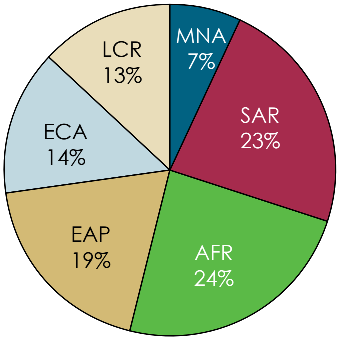
Figure 6.5 World Bank's water lending and number of projects for FY06–08 and FY09–10



The water portfolio continues to be dominated by projects that primarily deliver water services (Figure 6.7). For the FY06–08 period lending for water services prevails over water management not only in volume (70%) but also in number of projects (63%). It is important to note that investments towards water services exceed investments in water resources for all Bank regions. For the active period, a good portion of the lending in water resources, is going to AFR ($926 million), followed by SAR ($703 million) and EAP ($364 million) regions. In terms of project number, there is a similar trend with AFR accounting for the largest share (26%) of water resources systems. Similar to water resources, the three regions with the largest investment in water services systems are EAP ($1,327 million), SAR ($1,241 million) and AFR regions ($1,128 million). In terms of number of projects, LCR (24%) leads with the most number of projects with water services systems closely followed by AFR (23%).

Urban water supply and sanitation active projects account for almost half of the total investments (45%) for the FY06–08 period. This pattern is seen in all regions, except for SAR, where irrigation and drainage systems dominate investment in the region. The second largest share of investments is in multi-purpose facilities (17%) followed by irrigation and drainage (16%), and rural water and sanitation (10%). A small percentage of the total commitments are directed towards other water systems such as flood control (6%), water resources management (6%), and watershed management (1%). It is of relevance to mention that most of investments in multi-purpose systems in the FY06–08 period are in AFR (48%) and SAR (38%), and most of the investments in irrigation and drainage, and rural water are in SAR (49% and 31% respectively).

Figure 6.6 Regional distribution of the World Bank water lending for the FY06–08



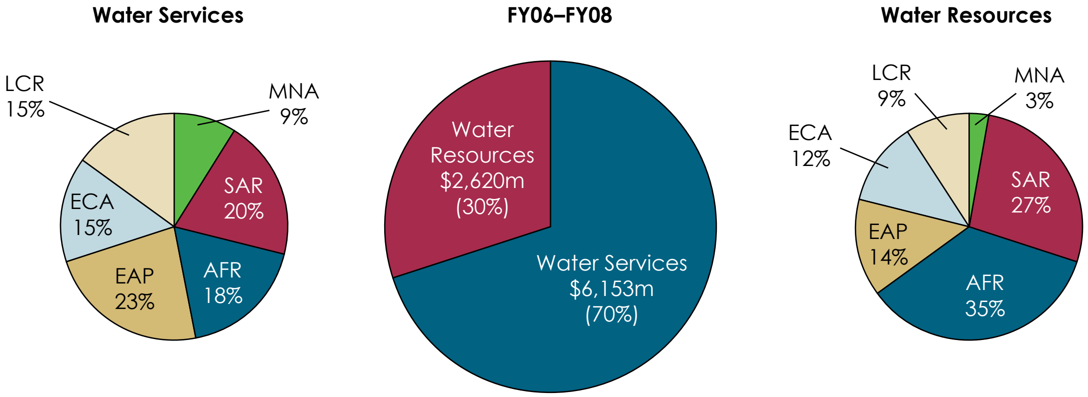
The pipeline[21] **follows a similar pattern with regards to distribution of lending by water systems. Projects involving delivery of water services are expected to constitute nearly 70% of the total lending in the pipeline.** Following the historical trend, urban water supply and sanitation systems are expected to lead in terms of lending volume (48%) while irrigation and drainage and multi-purpose facilities are also expected to account for a considerable portion of the pipeline (16% and 13% respectively). The pipeline shows growth in investments, with the average yearly lending expected to almost double compared to the FY06–08 period. Most regions are projected to have an increase in water investments, notably the LCR, EAP and SAR regions. Although AFR is showing a small percentage decrease in terms of water investments (yearly average) for FY09–10, there is a considerable increase in terms of number of projects per year. The largest share of projects in the pipeline is in AFR (25%), followed by LCR (23%) and EAP (19%) regions.

Climate change content of the portfolio

Adaptation to climate change in the portfolio

The portfolio and the pipeline were reviewed to determine whether hydrologic variability and climate change actions are considered and if so, to what degree incorporated into

Figure 6.7 Lending distribution in water services and water resources for the FY06–08



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[21] Pipeline results should be considered with caution because of the changes in approval dates, commitment amounts, etc, during the preparation phase of the project.

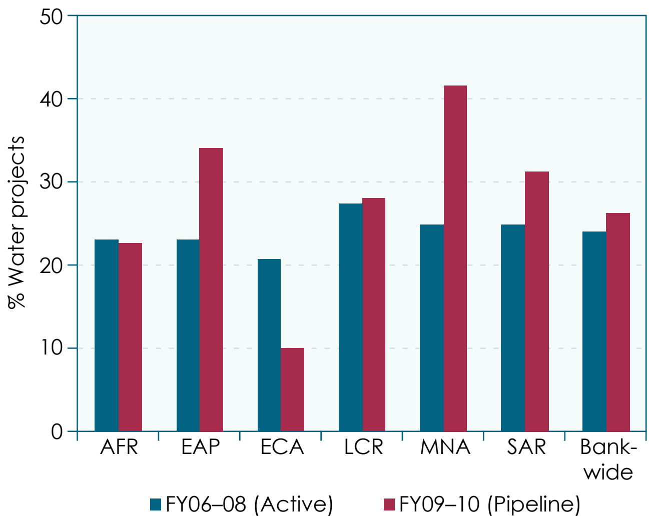
the design of projects. This review does not attempt to assess the efficacy of those interventions, but rather, attempts to give a general idea of whether climate change is reflected in the current and future portfolio of the water sector. Climate interventions are identified and distinguished between mitigation and adaptation measures. Adaptation is further classified in two broad categories—'no regret' and 'climate-justified', and further grouped into several areas of intervention.

Review of the portfolio suggests an increasing level of attention to climate change. The review of water projects for inclusion of mitigation and adaptation measures yielded the following results. Of 191 active projects approved in FY06–08, 35% (67 projects) considered strategies to reduce the impacts of climate variability and change, including adaptation and/or mitigation measures. Of the 67 projects with some strategy, 58% are related to adaptation, 31% related to mitigation and 10% related to both.

Water sector projects are primarily focused on adaptation. For the active portfolio, 20% of the projects addressed climate variability and change through adaptation measures. On average, there were 13 projects with potential adaptation actions each year for the FY06–08 period, with a promising growth expected for the FY09–10 period. Of the 20% of projects taking adaptation measures, it is important to note that these measures address, for the most part, strategies to reduce vulnerability to climate variability more than looking at the long-term effects of climate change. Of the total number of projects at the regional level, LCR had the largest portfolio with adaptation measures (28%) followed by SAR (25%) and MNA (25%) (Figure 6.8). The pipeline shows an increased attention to the adaptation agenda for most regions, with MNA and EAP in the forefront in terms of considering adaptation measures in their overall pipeline of projects. Although MNA shows a high percentage of adaptation measures in the active portfolio and pipeline, the total number of projects (with and without adaptation) is very low compared to other regions. Overall, there is clearly a higher level of awareness among the Bank and client countries towards climate change and climate variability issues. Note that the pipeline results should be viewed with caution as there is some degree of volatility with regards to approval dates, commitment amounts, etc.

The mitigation agenda is more visible in the energy sector than the water sector, but increasing attention is given to how the sector can contribute to the reduction of greenhouse gases. Of the total active portfolio, 11% of the actions were aiming at reducing greenhouse gas emissions. Only projects in which the role of low carbon technology, as well as the reduction of greenhouse gas emissions, are explicitly mentioned in the documents are classified here as mitigation projects. Many mitigation strategies are also linked to adaptation, such as the case of some hydropower projects. Some examples of mitigation measures

Figure 6.8 Projects with potential adaptation measures (%)



identified are improvement of energy efficiency of water supply systems (e.g. replacing pumps), wastewater treatment technologies to reduce methane emissions, mangrove carbon sequestration, methane collection in anaerobic lagoons, restoration of natural drainage regime for carbon sequestration, and so on. The reduction of carbon emissions in these projects is for the most part linked to carbon finance investments, which is a strong business at the Bank.

The portfolio shows two broad categories of actions: 'no regret' and 'climate justified'. Many of the actions to reduce vulnerability to climate variability are no different in a world with climate change than they are in a world without it. These actions are called 'no regret' and some examples include reform, institutional and infrastructure measure to increase water use efficiency and productivity, such as water-conserving irrigation technologies; increased water availability through storage and better management of bulk water; wastewater recycling; economic incentives, including pricing; and the encouragement of water markets that move water to high-valued uses. These options carry 'no regrets' in that they would go a long way in confronting the climate change challenges, yet they are by definition justifiable even under expected climatic conditions without anthropogenic climate change. On the other hand, other actions might be justifiable under conditions of anthropogenic climate change. 'Climate-justified' actions include those taken solely for the purpose of adapting or coping with such impacts. Those typically include constructing new infrastructure (dams, underground storage, irrigation systems), retrofitting existing infrastructure, changing rules of operation, tapping new sources of water, water transfers, conjunctive use of surface and groundwater, innovative demand management, etc. It should be noted that some of these action types may be "no regret" in one set of circumstances and "climate justified" in another.

The review shows strong emphasis on 'no regret' actions, with 67% of the adaptation projects adopting measures that meet current economic, social and environmental objectives but also serve the dual purpose of reducing vulnerability to climate change. At the regional perspective, most of the 'no regret' actions are in AFR and LCR. The pipeline follows the same pattern, with 'no regret' actions prevailing over 'climate-justified', and showing a distribution of actions prevailing in AFR, EAP and LCR.

'Climate-justified' actions are less predominant in the portfolio, representing 33% of the adaptation projects, or 8% of all active projects. For the FY06–08 period, most of these actions were concentrated in LCR and EAP. Examples of actions include—mainstreaming climate change considerations in public policy; institutional consolidation of flood control for a medium and long-term intervention strategy (to help the country adapt to sea level rise); implementation of pilot adaptation measures for wetland restoration strategies, implementation of climate resilient measures such as rainwater harvesting, creating better capacity and awareness among farmers for adoption of new techniques for coping with the effects of climate change; among others. The pipeline shows a larger percentage of projects with 'climate-justified' measures, most of which are in LCR, SAR, and EAP.

Types of Adaptation Interventions as Identified in the Portfolio

Building resilience to current climate variability or adapting to future climate change will require interventions in several areas. Some of the overarching areas[22] highlighted in this review are: policy/institutions, management/operations, infrastructure, technology/innovation,

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[22] Categories identified from a broad range of specific actions to facilitate presentation and utilization of report. These are consistent categories found in public literature. These categories are not exhaustive.

capacity building/awareness and monitoring/information systems (Figure 6.9). To increase water security stronger institutions are needed, as well as more investments in infrastructure (small and large), and new technologies for increasing water use efficiency. Moreover, better water management and operations, coupled with stakeholders capacity building and enhanced monitoring and information systems, are also essential elements for adapting to climate change.

Figure 6.9 Types of climate change interventions

Type of Intervention	
Policy/Institution	Technology
Water Management	Monitoring/Information systems
Infrastructure	Capacity building awareness

For the active and the pipeline[23] periods, policy/institution interventions dominate with 27% and 33% of the adaptation actions respectively (Figure 6.10). Projects with these interventions are mostly concentrated in AFR, LCR and SAR for the active period. These involve institutional strengthening and capacity for multi-sectoral planning, development and management of water resources. More specifically, these actions support policy, legal and regulatory environment for the efficient and sustainable management of water resources. In some cases, the institutional interventions are more specific to climate as to developing climate change policy or adaptation strategies. Having strong institutions with the right institutional framework is a first step towards adapting to changes in climate.

Specific examples of adaptation options in the portfolio with policy/institution intervention are listed below without any particular preference on ranking:

- Consolidate and improve water resource management and policy through institutional strengthening and improved planning, regulation and financing instruments.
- Strengthen the institutional and policy development capacity of the water agency within an integrated water resources management framework by preparing, enhancing and implementing water basin plans.
- Improve institutional capacity for basin-scale, participatory, integrated WRM for the newly created National Water Authority, and formulate a national strategy for water quality management.
- Strengthen institutional capacity for managing shared trans-boundary natural resources.
- Institutional consolidation of flood control to create a consensus around a medium and long term intervention strategy to adapt to sea level rises.
- Strengthen institutional capacities to reduce vulnerability to the natural and manmade hazards and to limit losses due to disasters.
- Mainstream climate change considerations in public policy as part of the National Climate Change Strategy.

Interventions related to management/operations are the second highest share for both periods, with AFR, ECA and LCR in the forefront in terms of adopting management

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[23] The pipeline results should be considered with caution and viewed as illustrative, as there are many projects for which documents were not available in the system.

instruments or tools for the effective operation and management of water systems. More specifically, projects with these actions include implementation of economic incentives such as water markets, water pricing; conjunctive management of groundwater and surface water; watershed and flood management planning, etc. A wide range of demand-side/supply-side management measures are considered which will help address the quality and availability of water resources, its efficient and equitable allocation to the various end-users, and help reduce the vulnerability to extreme climatic events and long-term climate change. It is worth mentioning that many projects adopted integrated water resources management (IWRM) frameworks. IWRM is an effective way to position water issues, address water quality and quantity aspects at the policy and local level, and at the same time play a major role in aiding societal adaptation to climate change. IWRM will likely decrease the vulnerability of freshwater systems to climate change.

Specific examples of management/operations interventions extracted from the portfolio are listed below without any particular preference on ranking:

- Implement improved water management practices, including bench marking, administration of water entitlements, and bulk supply of water to users.
- Participatory and integrated ecosystem management by carrying out programs to implement integrated watershed and wetlands management strategies.
- Restore operational performance and safety of dams.
- Develop and strengthen key WRM instruments such as the formulation of a detailed participatory and integrated WRM plans for basins, bulk water distribution models and decision aid tools.
- Optimize water resource utilization and enforce water use rights.
- Implement conjunctive management of groundwater and surface water.
- Invest in watershed development and flood management for climate resilience.
- Increase water flows in rivers through conservation of the paramos ecosystem and its associated vegetation.
- Implement cyclone risk mitigation investments through mangrove plantations and coastal zone management works.
- Develop new sustainable financing mechanisms for the payment of environmental services (watershed conservation) through water tariff.

Infrastructure interventions are also represented in the active and pipeline projects with most interventions in LCR, SAR, EAP and AFR. Water infrastructure is defined by the rehabilitation, optimization and development of small and large hydraulic infrastructure to improve the management of water resources and delivery of water services by making the systems more resilient to the changes in climate. Some examples include—retrofitting existing infrastructure; developing multi-purpose storage and attenuation structures; creating long-term structural solutions to flooding; rehabilitation of irrigation schemes, etc. It is important to note that infrastructure rehabilitation for projects categorized as recovery or emergency operations are not included in this class.

Specific examples of infrastructure interventions extracted from the portfolio are listed below without any particular preference on ranking:

- Rehabilitate and modernize water infrastructure (irrigation, hydropower, etc).
- Create long-term structural solutions to flooding, including the construction of substantial multi-purpose storage and attenuation structures.

- Develop hydropower resources in an environmentally sustainable and socially responsible manner.
- Build long-term preparedness by supporting cyclone-resistant infrastructure rehabilitation, livelihood restoration and vulnerability reduction.
- Support the construction and/or installation of storage/conveyance structures and distribution networks to optimize the storage, delivery, and use of water supplies.
- Build water harvesting infrastructures, including valley dams and reservoirs, and hillside irrigation infrastructure.
- Develop groundwater infrastructure in a sustainable manner.
- Develop small-scale storage structures, crop diversification and water harvesting for farmers.

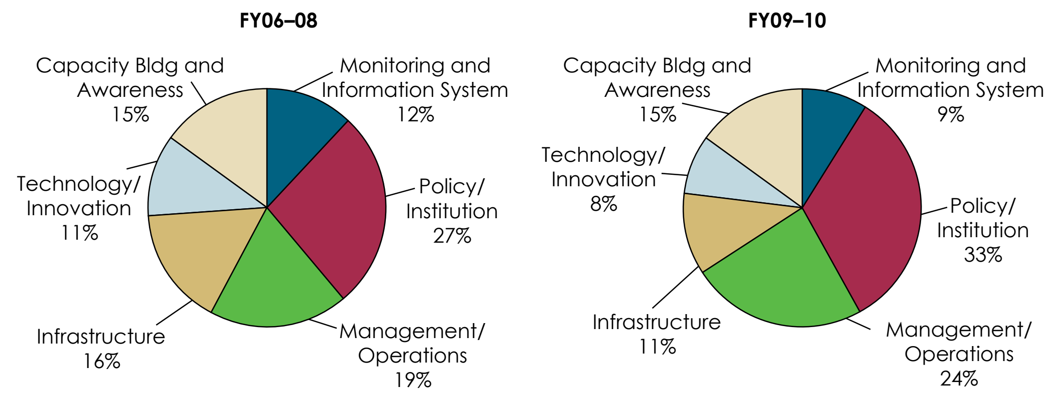
Capacity building and awareness are also important elements for the effective management and decision making of water resources, as well as for adaptation to climate change. With most interventions in AFR, LCR, EAP and SAR, these actions will build local capacity and raise awareness for water users and communities about how they can play an expanded role in the management and decision making of water resources and adaptation to climate change. This is achieved by building local capacity; empowering water users and water users' associations; engaging communities in the decision framework, offering trainings, and implementing awareness-raising campaigns at the community and user level to promote greater responsibility in managing water resources in view of the changing climate conditions.

Specific examples of this type of intervention taken from projects in the portfolio are given below without any particular preference on ranking:

- Technical assistance for water sector capacity building to carry out water resources investment planning.
- Increase climate change adaptation awareness of water user associations, technical staff, and officials.
- Increase civil society participation in the decision making process for water resource management.
- Empower water users and strengthen water user associations in order to enhance their capacities, and carry out necessary operation, maintenance and cost recovery functions.
- Promote participation of local governments, concerned agencies and stakeholders in improving flood management plans.
- Engage communities in co-management of water and forest resources.
- Create a participatory approach to sustainable watershed management by formation of community associations to manage watershed conservation plans.

With a moderate representation in the portfolio, EAP, SAR and ECA are the regions that have invested the most in monitoring and information systems. Monitoring and information system interventions are vital actions to better forecast and monitor hydrological variability in water systems for the efficient, sustainable and equitable management of water resources and adaptation to climate change. Actions include the development and improvement of water resources information systems with monitoring, modeling and prediction capabilities, weather forecasting, hydro-meteorological data collection, early flood warning and response systems, etc. Any action involving analysis of hydrological trends and improvement in the accuracy of forecasting methods is key for effective management of water systems and for the design of new ones. This type of intervention is essential for long-term planning, and especially for detecting and quantifying the impacts of climate change.

Figure 6.10 Type of intervention for projects in FY06–08 and FY09–10



Specific examples on Monitoring/Information System interventions extracted from the portfolio are listed below, without any particular preference on ranking:

- Upgrade flood and storm monitoring; modeling and forecasting capabilities; and enhance early warning and response systems.
- Strengthen capacity in data analysis, mapping and vulnerability assessments.
- Strengthen water quality monitoring laboratories.
- Develop hydro-meteorological forecasting systems.
- Develop vulnerability and ecological mapping (including vulnerability to flood and erosion), and create demarcation of hazard zones susceptible to natural disasters and flooding.
- Establish a telemetry system for real-time measurement of water availability.

Technology as an adaptation measure has much unexploited potential for scaling up. The adaptation interventions are more prominent in AFR, EAP and LCR with a wide variety of measures aiming to increase water use efficiency, or incorporation of new technologies to make water systems more resilient to climate variability and change. Some examples include the adoption of water saving technologies such as treated wastewater reuse, water harvesting, evapo-transpiration-based water resources planning, or any other innovative measure to increase water use efficiency. Some technologies are applied at the pilot level for later implementation at a larger scale.

Specific examples of technology interventions extracted from the portfolio are listed below without any particular preference on ranking:

- Develop water-saving technologies (e.g. drip irrigation).
- Promote treated wastewater reuse in irrigation on a sustainable basis.
- Improve irrigation systems by enhancing water use efficiency in tank areas.
- Develop improved irrigation technology including pressurization of surface flows to replace groundwater.
- Adopt evapotranspiration measuring technology.
- Adopt soil and water conservation technologies.
- Develop water harvesting techniques.

CHAPTER 7:
EXPOSURE OF THE WATER PORTFOLIO TO CURRENT HYDROLOGIC VARIABILITY AND FUTURE CLIMATE CHANGE

Introduction

The World Bank's investments in the water sector are highly exposed, both to current variability and future climate change. The purpose of this assessment is to provide some sense of magnitude of the exposure of the projects and the financial investments they represent. Results of the projections of the hydrologic drivers for 2030 and 2050, discussed earlier, are used to assess the exposure of the portfolio. In this chapter, investment exposure to the impact of climate change for the following water systems is assessed: irrigation and drainage, urban water supply and sanitation, rural water supply and sanitation, flood control, river basin management, and multi-purpose (supply water for multiple purposes).

Risk is generally defined as the product of probability and consequence. Given that the probabilities of occurrence of different climate change scenarios are not known, a formal risk assessment cannot be carried out. Rather, an evaluation of the impacts of climate change on Bank investments is carried out in terms of changes in hydrologic indicators and changes in the level of exposure of the investments to these indicators. In this context, exposure is loosely equated to consequence.

For this assessment the A1B emissions scenario is chosen. This scenario is suggested by many to be the closest to a "business as usual future". Additionally it is the middle range of emissions and resulting global mean temperature of all the AR4 SRES scenarios as discussed earlier. Given that the interest here is a broad overview of the potential exposure of World Bank infrastructure projects particularly those with the life extending to 2050, the A1B scenario provides the central tendency of scenarios to the year 2050. Additionally all the scenarios are tightly bunched until 2050 where at that point they start to diverge greatly.

Hydrologic indicator selected for assessment of each water system is given in Table 7.1. These indicators have been defined earlier in connection with the projections analysis. An indicator has been chosen to represent each water system as listed below.

Table 7.1 List of water systems and indicators

Water System	***Indicator***
Irrigation and Drainage	Change in annual net irrigation deficit
Urban Water Supply and Sanitation	Change in runoff reliability
Rural Water Supply and Sanitation	Change in minimum base flow
Flood Control	Change in runoff reliability
River Basin Management and multi-purpose infrastructure	Change in basin yield

Exposure criteria and investment exposure

Each water sector is given an exposure level based on an agreed exposure criteria. For the current variability analysis, the exposure level represents the water sector's exposure to current variability. For the future exposure analysis, the exposure level represents the water sector's exposure to climate change and future variability. The exposure criteria is categorized as low, medium or high. A low exposure level means that there is little to no concern about the water sector's exposure to current/future climate variability/change, where a high exposure level means that there is an immediate concern. A medium exposure level means that there is some concern and further analysis is necessary. The ranges for the low, medium, and high exposure level classifications were determined for each indicator.

Exposure of the World Bank's investment portfolio to future climate change is evaluated using the exposure level for each system and placing the investment (lending) value on that exposure. The investment exposure is calculated by multiplying the cost of each project allocated to the water system times the number of GCM results that fall into each of the three exposure criteria—low medium, or high. Results for each exposure class were summed to yield regional values. The total investment value for each region is the sum of the cost of each water system in each project.

Results of current and future exposure to variability and climate change are reported by World Bank regions and Bank-wide. The exposure is represented as low, medium, or high as previously discussed. Results of investment portfolio exposure are by water system, World Bank regions and the World Bank as one region. The investment portfolio exposure is reported as monetary amounts. Future exposure based on climate change is reported for 2030 and 2050. These years were chosen because they represent times in the future that are important for current infrastructure planning intersected with the expected realization of potential climate change impacts. For this analysis, reporting changes in 2030 relative to historical is the decadal average from 2025 to 2035 relative to the average historical. This is also true for reporting 2050; represented by the average from 2045 to 2055 relative to the average historical.

Exposure to current hydrologic variability and future climate change

For each project on the review list, an approximate latitude and longitude was estimated based on the information available in the project documents. For projects with multiple locations, only one location was selected based on the size of the city or population and its proximity to the water source. Each project was then mapped to a 0.5 degree by 0.5 degree grid on the globe. The percentage change of the related hydrologic indicator for the projected hydrologic variables for 2030 and 2050 was also mapped on the same grid as the project location for assessment of the exposure. Assessment of exposure for each water system for each region is described and the results reported in the subsequent sections.

A word on the limitation of this approach. It should be noted that this analysis is focused on the future changes of the mean of the hydrologic drivers only, as they are derived from the mean runoff projections. In many cases the future changes of variability in runoff may be much more important than the change in the mean. Many projections show increases in variability which lead to more extreme events. For example, a 10% change in runoff variance may be much more important (potentially many times more damage) than a 10% change in the mean runoff. Evaluating the impacts of variability on investments is outside the scope of this analysis, but should be highly considered for future work.

Irrigation and drainage

Irrigation and drainage is represented by the change in annual net irrigation deficit. This is determined using the Water Deficit Index (WDI) which is the difference between the precipitation and crop water requirement. Table 7.2 shows the criteria used to assess the levels of exposure. Figure 7.1

shows the exposure map for 2030 for the middle projection for all Bank regions. Figure 7.2 shows exposure map for 2030 and 2050 for the driest, middle, and wettest projections for the Africa region.

Table 7.2 Irrigation and drainage exposure level descriptions

Exposure Level	**Description**
Low	% change in annual water deficit index < 5%
Medium	% change in annual water deficit index between 5% and 15%
High	% change in annual water deficit index >15%

Urban water supply and sanitation

Urban water supply and sanitation is represented by the change in runoff reliability. Runoff reliability is determined using a flow duration (frequency) curve (FDC). A FDC is generated by plotting the percentage of time that a flow rate is greater than or equal to a given flow rate. This indicator is taken as the flow that is exceeded 90% of the time (q90) which means there is a 10% chance in each time period of a flow lower than this. If this q90 decreases it means that the likelihood of low flows and droughts will likely increase. Table 7.3 shows the criteria used to assess the levels of exposure. Figure 7.3 shows the exposure map for 2030 for the middle projection for all Bank regions. Figure 7.4 shows the exposure map for 2030 and 2050 for the driest, middle, and wettest projections for the Africa region.

Table 7.3 Urban water supply and sanitation exposure level description

Exposure Level	**Description**
Low	% change in runoff reliability(–90%) >–5%
Medium	% change in runoff reliability(–90%) between –5% and –15%
High	% change in runoff reliability(–90%) <–15%

Rural water supply and sanitation

Rural water supply and sanitation is represented by change in minimum base flow as a proxy for groundwater availability. It is assumed that the groundwater contribution to runoff can be model as a "linear reservoir" where base flow is combination of a groundwater-surface water interaction coefficient multiplied by the groundwater storage in the month. Table 7.4 shows the criteria used to assess the levels of exposure. Figure 7.5 shows the exposure map for 2030

Table 7.4 Rural water supply and sanitation exposure level description

Exposure Level	**Description**
Low	% change in minimum base flow >–5%
Medium	% change in minimum base flow between –5% and –15%
High	% change in minimum base flow <–15%

for the middle projection for all Bank regions. Figure 7.6 shows the exposure maps for 2030 and 2050 for the driest, middle, and wettest projections for the Africa region.

Flood Control

Flood control is represented by the change in runoff reliability. Runoff reliability is determined using a flow duration (frequency) curve (FDC). A FDC is generated by plotting the percentage of time that a flow rate is greater than or equal to a given flow rate. This indicator is taken as the flow that is exceeded 10% of the time (q10) which means there is a 90% chance in each time period of a flow lower than this. If this q10 increases it means that the likelihood of higher flows and floods will likely increase.

Table 7.5 shows the criteria used to assess the levels of exposure. Figure 7.7 shows the exposure map for 2030 for the middle projection for all Bank regions. Figure 7.8 shows the exposure maps for 2030 and 2050 for the driest, middle, and wettest projections for the Africa region.

Table 7.5 Flood control exposure level description

Exposure Level	Description
Low	% change in runoff reliability(-10%) <5%
Medium	% change in runoff reliability(-10%) between 5% and 15%
High	% change in runoff reliability(-10%) >15%

River basin management and multi-purpose infrastructure

River basin management is represented by the change in basin yield. The basin yield is a measure of annually reliable water supply from the basin. Basin yield is directly related to the amount of reservoir storage in a basin. A storage-yield curve is used to mathematically represent the basin yield. Table 7.6 shows the criteria used to assess the levels of exposure.

Figure 7.9 shows the exposure map for 2030 for the middle projection for all Bank regions. Figure 7.10 shows the exposure maps for 2030 and 2050 for the driest, middle, and wettest projections for the Africa region.

Table 7.6 River basin management exposure level description

Exposure Level	Description
Low	% change in basin yield <5%
Medium	% change in basin yield between 5% and 15%
High	% change in basin yield >15%

Note: Historic Yield = 75% of Historical Annual Runoff

Figure 7.1 Projected 2030 exposure map to change in water deficit index

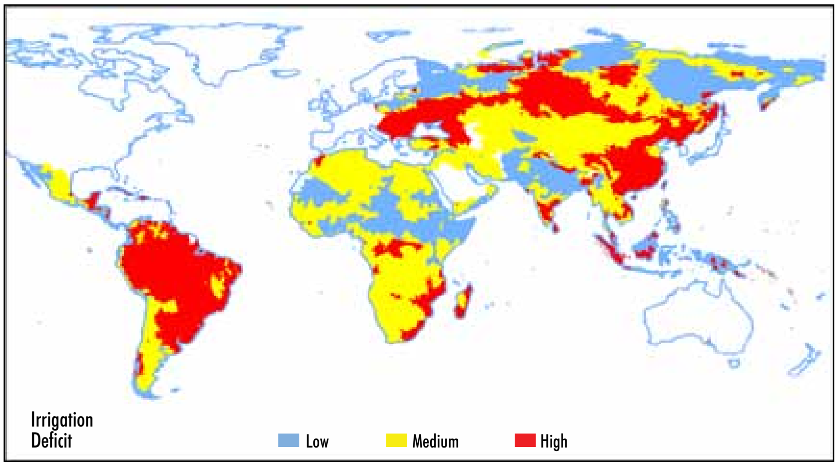


Figure 7.2 Projected 2030 and 2050 exposure maps to change in water deficit index – Africa Region

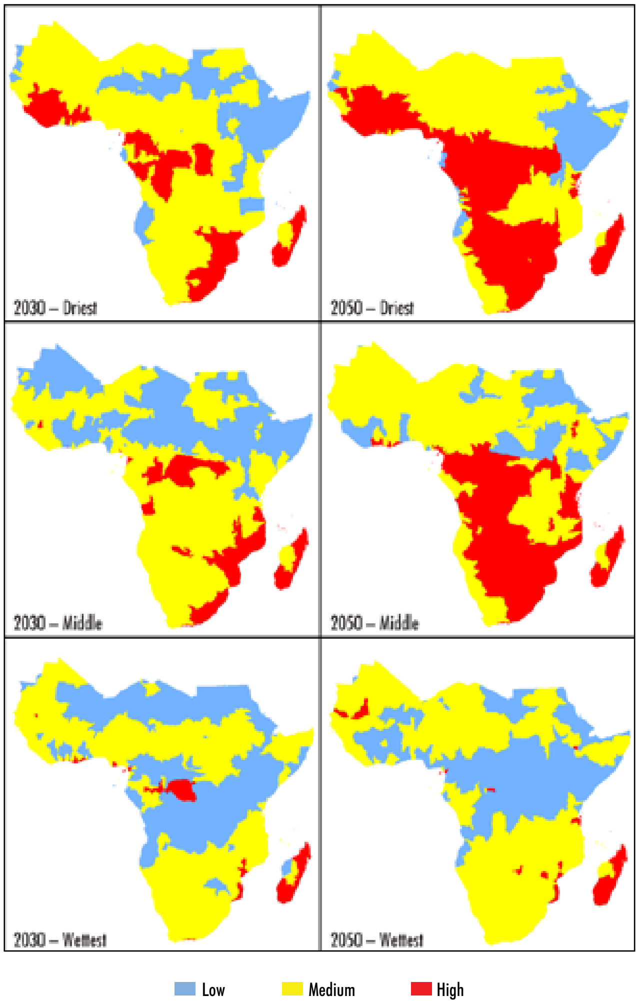


Figure 7.3 Projected 2030 exposure map to change in low flows (drought)

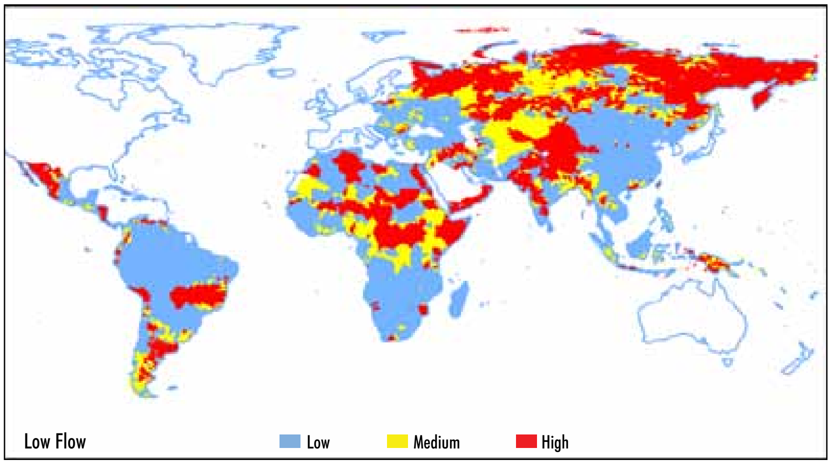


Figure 7.4 Projected 2030 and 2050 exposure maps to change in low flows (drought) – Africa Region

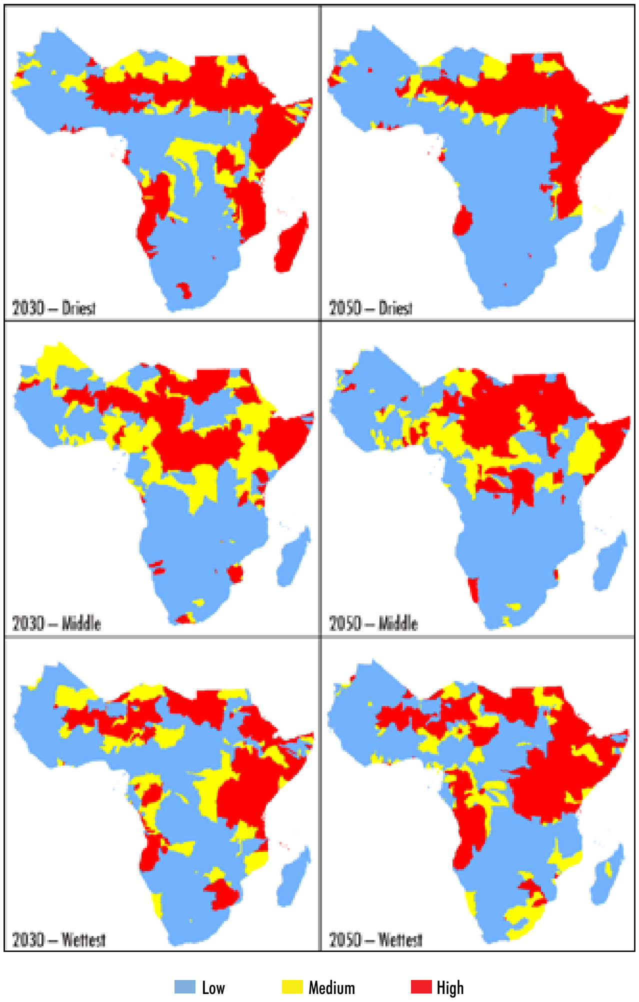


Figure 7.5 Projected 2030 exposure map to change in base flow

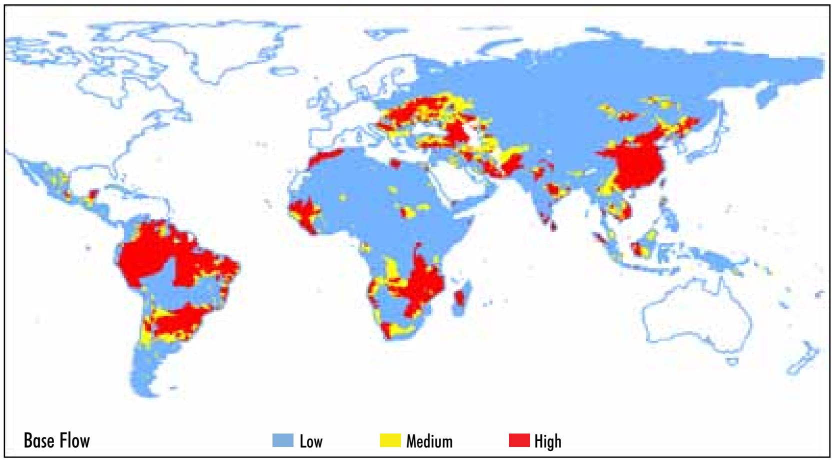


Figure 7.6 Projected 2030 and 2050 exposure maps to change in base flow – Africa Region

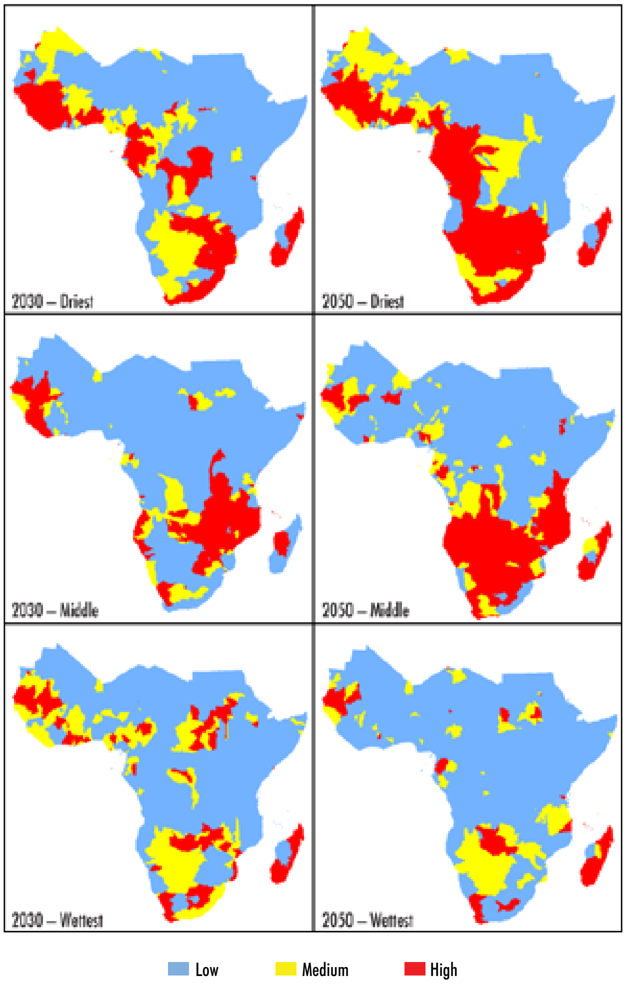


Figure 7.7 *Projected 2030 exposure map to change in high flows (floods)*

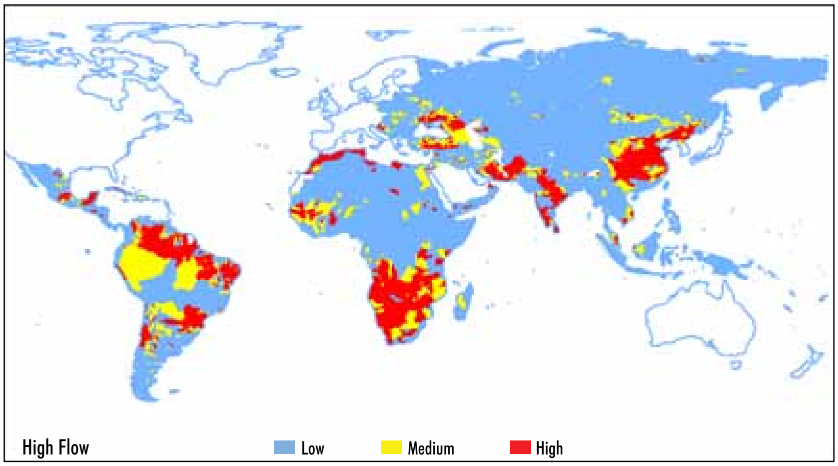


Figure 7.8 *Projected 2030 and 2050 exposure maps to change in high flows (floods) – Africa Region*

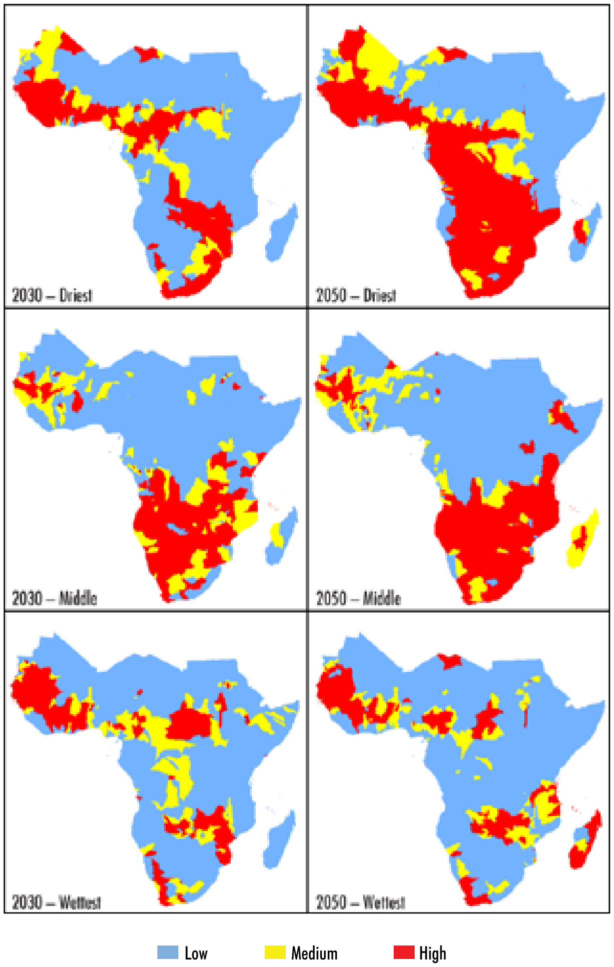


Figure 7.9 Projected 2030 exposure map to change in basin yield

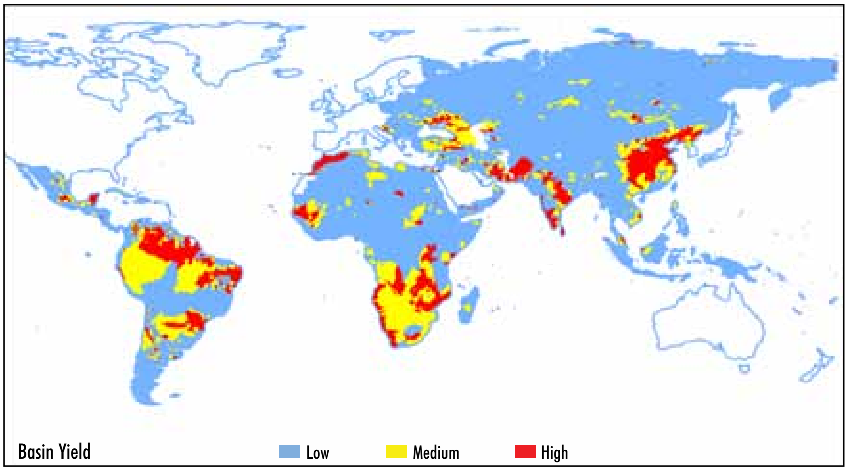
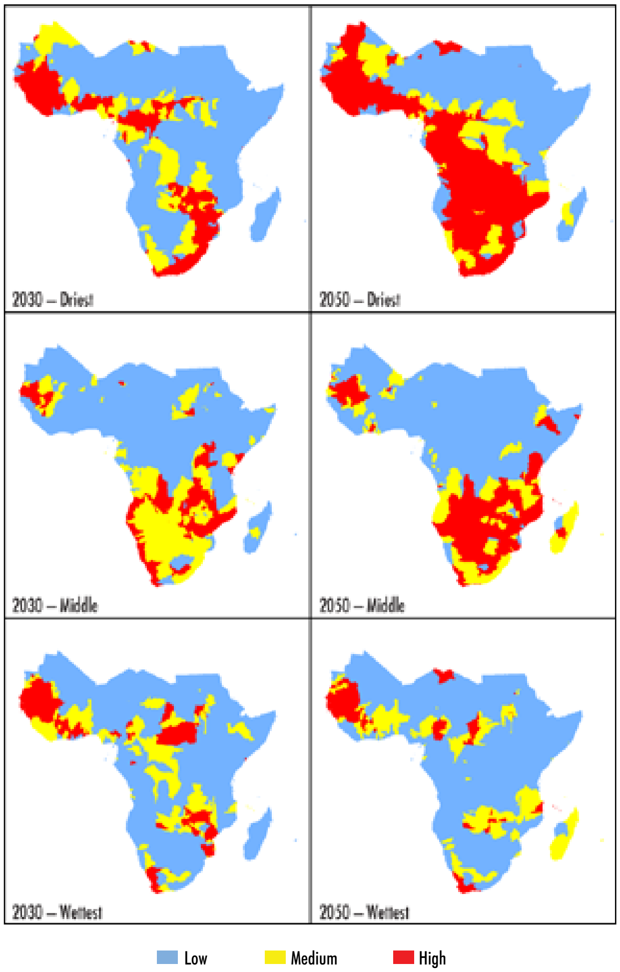


Figure 7.10 Projected 2030 and 2050 exposure maps to change in basin yield – Africa Region



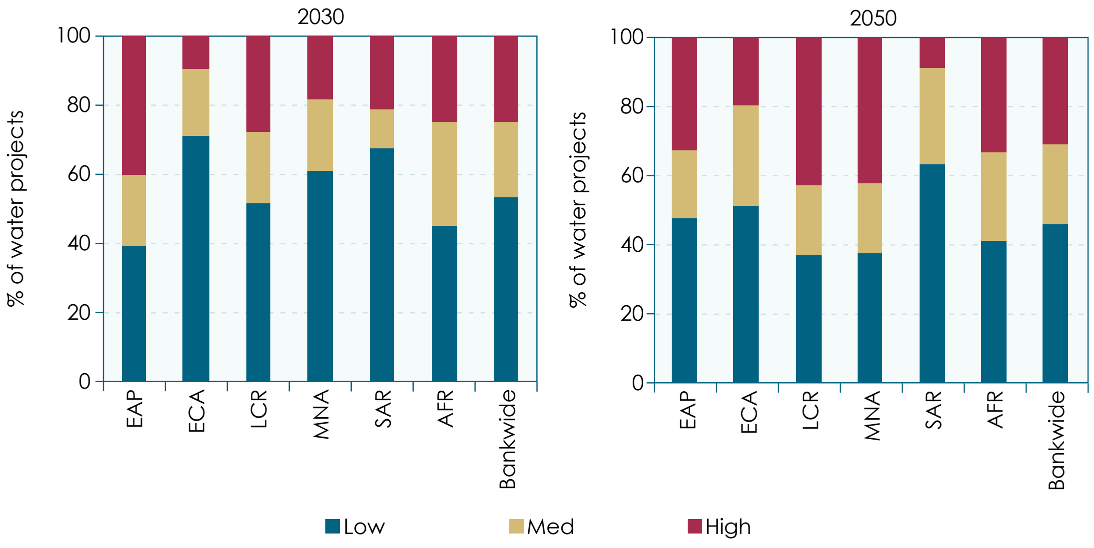
Potential exposure of the investment portfolio

The World Bank's investments in the water sector are highly exposed, both to current variability and future climate change. The purpose of this assessment is to provide some sense of magnitude of the exposure of the projects and the financial investments they represent. Using threshold criteria for changes in each indicator, maps were created for high, medium, and low exposure categories for each indicator. Water projects, classified by water systems, are superimposed on the appropriate exposure map. The outcome is an exposure categorization of each water system according to its respective indicator. In this analysis, exposure to the impact of climate change for the following water systems on the Bank portfolio is assessed: irrigation and drainage, urban water supply and sanitation, rural water supply and sanitation, flood control, river basin management, and multi-purpose (supply water for multiple purposes). Results of the potential exposure of the active Bank water investments were they to operate in 2030 and 2050 are available.

Bar charts on Figures 7.11 and 7.12 show the level of exposure of the Bank water investments to climate change by volume of investment and number of projects by region and Bank-wide. Similar charts, categorized by water systems, are available for each region and Bank-wide.

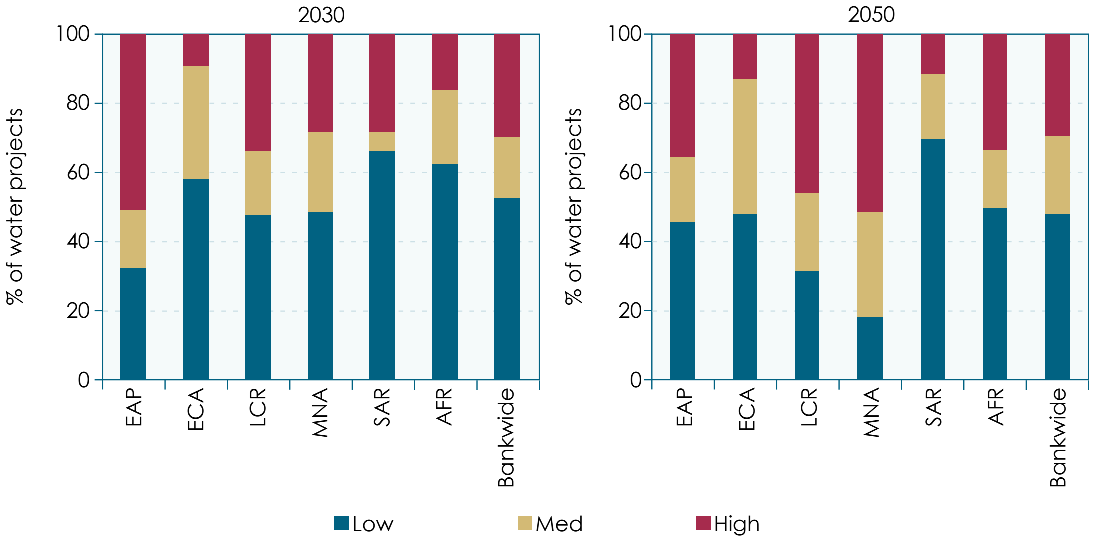
Projections indicate that about half of the Bank water projects reviewed would potentially be at high to medium level of exposure to climate change impacts in 2030 (Figure 7.11). Within each regional portfolio, EAP shows close to two-third of projects with potential exposure to high/medium risk, possibly due to increased flooding. AFR and LCR show about half of the projects and MNA some 40% at potential high to medium risk of exposure. ECA and SAR show about one-third of the projects at potential risk of exposure to hydrologic changes. Projections for 2050 show exposure increasing for all regions except EAP. Obviously, the level of uncertainty related to projecting climate change so far in time would be too high to make much of this difference.

Figure 7.11 Exposure of water projects to climate change in 2030 and 2050



In terms of investments, about half of the total water investments (including the pipeline) are projected at high/medium exposure level to climate change impacts in the 2030 decade (Figure 7.12). This translates to approximately $ 10 billion on the FY06–10 water projects reviewed here, risk associated with approval, delay, or drop of pipeline projects notwithstanding. The pattern of risk of exposure of investment roughly follows that of the projects. For 2050, climate change projections show an increase in MNA, AFR, LCR, and ECA, while expected to decrease in EAP, and SAR. Again, the uncertainty associated with the climate change projections in 2050 is considered quite high and therefore this conclusion should be viewed with caution.

Figure 7.12 Exposure of water investments to climate change in 2030 and 2050



CHAPTER 8:
RISK-BASED DECISION MAKING FOR 'CLIMATE SMART' INVESTMENTS

Introduction

There is evidence of an intensification and acceleration of the hydrologic cycle due to climate change, but this is subject to a high degree of uncertainty. Analysis in the previous chapter illustrates the exposure of the Bank's water investments to the potential impact of hydrologic variability and climate change. While the best available science was used, there is still substantial uncertainty regarding the real effects of climate change, generally, and by extension on the hydrologic cycle and ecosystem responses. There have been major advances in projecting impacts—both from general circulation models and downscaling/statistical methods—which allows reporting general trends with some degree of confidence (including in temperature, precipitation, and extreme events). However, there are still significant unknowns, and even more challenging "unknown unknowns". There is no way around these uncertainties given the current state of the science—even agreement on a particular phenomenon across multiple models does not 'prove' that a given projection will indeed come to pass.

Reducing the water sector's vulnerability to climate change means managing water under conditions of uncertainty. There are three options for dealing with uncertainties (i) wait until science is "better" at making projections; (ii) insist on pushing modeling efforts to their limits, and beyond; and (iii) take uncertainty as a given and try manage it. The first, wait and see, approach could be dangerous and costly in the longer run.[24] The second could also be hugely risky, that is, such an approach could lead to projections and actions based on them that are 'precisely wrong.' It is the third that holds the most promise. This approach is relevant to all sectors, but it is particularly so in the case of the water sector because of the direct link between climatic conditions and hydrology and environmental sustainability.

Water professionals have traditionally dealt with climate variability, but climate-change introduces uncertainties in both the future mean values and variability. Water professionals have routinely dealt with natural climate variability (inter and intra-annual) and climate-related hazards such as droughts and floods in delivering water services and managing water resources. But, they have historically done so under the key assumption of a stationary hydrologic pattern: the mean, variance and standard deviation of hydrologic time series is fixed over time. This assumption enabled decision-makers to estimate hydrologic risks to water systems, or, in other words, to establish with some degree of certainty both potential outcomes/impacts and the probability of their occurrence. Climate change introduces new uncertainties, both in respect to the future mean values and variability, but also in respect of uncertainty and the chance of outcomes that may be very different from any historic experience.

Climate change calls into question the classical assumption that past hydrologic knowledge provides a good guide to future conditions in planning, designing and operating water investments. It is now well-accepted that the future hydrologic regime will not be a statistical replica of the past, but there are significant unknowns as to precisely how hydrologic characteristics will change. Thus, the challenge confronting water professionals is

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[24] Indeed, Thomas Schelling, winner of the 2005 Nobel Prize in Economics, notes that the idea that actions are unwarranted if the dangers are uncertain is almost unique to climate change. In other areas of policy, such as terrorism, nuclear proliferation, inflation, or vaccination, some 'insurance' principle seems to prevail: if there is sufficient likelihood of significant damage, typically some measured anticipatory action is taken. (Economists' Voice, *www.bepress.com/ev*, July 2007).

how to plan, design and manage when the confidence in calculations of risk are substantially lowered because either the potential outcomes or the probability of their occurrence—or both—are largely unknown. There are—and have always been—many sources of uncertainty other than hydrology that are important to water management, including changes in population, income levels, technology, ecosystem functions and services and societal values. However, it is the increase in *hydrologic uncertainty* and the reduced ability to calculate *hydrologic risks* that make water management with and without climate change fundamentally different.

Water investment planning, design and operations require a formal risk-based analysis in all aspects of the project/program cycle. Water systems are subject to both climate and non-climate related stresses, but there are certain types of water investments where uncertainties related to climate change could have a significant impact, and so particular care needs to be taken in undertaking a detailed, rigorous risk assessment. These include highly capitalized or unique projects, irreversible investments, engineering structures with long lifetimes, long-lived benefits and costs, etc. Examples include: single and multi-purpose hydraulic infrastructure, interbasin water transfer schemes, water conveyance systems for irrigated agriculture, and regional/transboundary investments. Yet, there are water systems that are inherently resilient to some degree of hydrologic variability and climate change, are not significantly impacted, or the consequents of impact can be readily remedied. In these cases, a less rigorous risk assessment (screening level) may be sufficient.

Bayesian decision analysis framework one that allows for explicit characterization of risks, options, and management of risks. The approach incorporates unfolding uncertainties over time and accounts for the performance of those options (Hobbs, et al, 1997). In Bayesian decision analysis, the 'decision problem' is structured as a decision tree, in this specific case for evaluating options under various climate scenarios. Uncertainty is incorporated through the use of subjective probabilities for the scenarios in evaluating the expected outcome of the options.

This chapter addresses the necessity for incorporation of a formal risk-based approach in water investments, the overarching themes/issues to be considered at various phases of project/program cycle, a framework for risk-based decision making adapted from the current state-of-the-knowledge, and how such a framework may be applied to the Bank's project cycle.

Sector investment decisions must be made under increased risk and uncertainty

Risk management is a good practice for water management that makes sense even if the climate were not a consideration. The application of risk management is more applicable when climate change is considered. Although we know the climate is changing and will continue to change, it is not possible to make a precise prediction as to exactly how and when climate will change. At best, a range of potential changes in climate can be identified. This wide range of potential changes in climate provides justification for applying principles of risk management to manage water resources. It is more imperative to consider the risks that climate change can bring and manage systems appropriately to reduce or minimize risks, particularly those of greatest concern.

Water managers now face unprecedented challenges to investments in and management of water resources and services. In the past, water managers often recognized that the systems they built and managed were vulnerable to hydrologic variability, population growth, and other pressures and challenges. The typical response to such vulnerabilities, however, was to factor in large margins of safety that reduced the risk of an adverse event (e.g., for potential water supply shortages—transfer water between river basins; for potential urban flooding—install high capacity storm water infrastructure). Furthermore, they assumed the climate was stationary—the likelihood and magnitude of extreme climate events as well as average climate conditions were known based on historical records. Thus, it was thought that systems could be designed and operated to better manage adverse events (e.g., inadequate water supplies, floods) by reducing the frequency and/or magnitude of failure. Past investment decisions have incorporated uncertain future trends, such as population movement from rural to urban areas shifting the geographical distribution of water demand, population growth increasing total water demand, new irrigation technologies increasing effective supply, new thermoelectric power plants causing spikes in water demand, the possibility of drought affecting water supply in any given year, and more. Many past water systems have successfully provided safe and reliable water supplies and other services despite these uncertainties—climate change simply adds one more uncertainty to the list water managers have successfully tackled for generations.

The margin of safety built into water projects often entails investing significant resources to avoid low probability, high consequence risks. The opportunity cost of factoring in such large safety margins was once non-controversial, but resource scarcity, escalating costs, and expansion in demand for water resources and services as well as increasing environmental and degradation and awareness have put significant pressure on water managers to reduce, manage or contain costs while expanding services. Consequently, the acceptable margin of safety for water resources and services has narrowed. Compounding these difficult realities, climate change adds a new challenge that further complicates the operational environment by replacing the conventional, stable, but variable, hydrological baseline with a new one to include changing average conditions as well as changing variability. However, this new baseline cannot be estimated with a great degree of certainty.

Current understanding of climate and climate change indicates that historical data is no longer the only reliable guide to future climate events.[25] Whereas scientists, engineers, and water managers previously considered the climate to be stationary, we now understand that climate is subject to a number of forces that cause averaged conditions and extremes to change over time. For example, engineers typically design flood control structures based on an engineering standard (e.g., design to withstand a 100-year flood) and historic stream flow and flooding data inform that standard (e.g., a 1% chance of flood waters exceeding 10 meters in any given year based upon 150 years of historical data). In other words, designing for a 100 year flood under the recent past might equate to designing for a 50 or even a 20 year event in future decades (or, alternatively, to design for the 100 year flood of the future, we may need to design for what we currently consider to be a 500 year flood).

Future decision making will be further complicated because climate is changing and the rate of that change is likely to accelerate. Even accounting for recent climate trends e.g., the observed rate of sea level rise, may not be sufficient to prepare for climate change. But, it is not possible to precisely forecast future climate conditions: we cannot precisely predict future emissions of greenhouse gases, nor can we accurately project the change in climate variables that will result from those changes in greenhouse gases, or the change in hydrology that will result

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[25] To be sure, climate has never been stationary. Climates have always changed for natural reasons such as changes in solar radiation, the earth's orbit around the sun, and other factors. What is new is the addition of human caused climate change.

from those changes in climate. This is particularly true at the geographic scale relevant to most water resources and services, which are typically managed at the river basin level, the individual water supply source, or the specific treatment facility or other water system. Consequently, water managers must always make investment and operational decisions under uncertainty.

The good news: making decisions under uncertainty is neither new nor unique to water investments. Making decisions under uncertainty requires an adequate accounting of the risks faced under different options and/or different projected future conditions. Armed with an understanding of the options available to them, water managers must weigh the tradeoffs associated with making alternative choices about which risks to reduce and which ones to bear. In some cases, a risk will be so unacceptable that the old paradigm of simply building in expensive safety factors may be the best choice (e.g., overbuilding dams to ensure they will not fail). In other cases, strategies exist to reduce the consequences of an adverse event while reducing the costs of a water investment (e.g., instead of retrofitting inadequate storm water drainage infrastructure, build above ground culverts and protect low lying land downstream from development to provide a natural floodplain). Such strategies, discussed below, allow for less expensive and oftentimes more effective water systems and services.

Given the policy, financial implications of making water investment decisions, a more systematic approach is needed for water investment decision making. We call the systematic approach proposed in this chapter *risk-based decision making*. Risk-based decision making considers uncertainty explicitly (not only applicable where 'risk' can be quantified) in the evaluation of probabilities and consequences associated with alternative investment strategies as well as strategies to make informed decisions in the face of irreducible uncertainty.

Water managers have two choices—to ignore the changing risks posed by altered climate and hydrology and rely only on historic data or to use risk-based decision making. In spite of the problematic uncertainty associated with changing climate baselines, precedents of risk-based decision making by water managers exist. This chapter first discusses risk-based decision making. It includes a discussion of tools for implementing a risk management approach and measuring vulnerability. Then, the chapter builds on the analysis of risk management to examine adaptation to climate change. The focus will be on the types of adaptations that make sense given what is known about climate change.

A framework for risk-based decision making for water investments

Definitions and terminology

According to the U.S. National Research Council, risk analysis has two components—risk assessment and risk management. Risk assessment is the factual basis for defining adverse events and determining their probabilities and consequences. Risk management is the process of weighing policy alternatives in response to risk. Risk assessment is further decomposed into risk identification—determining whether a particular event has adverse consequences, and risk characterization—describing the nature and magnitude of the risk (NRC 1983, 1994). However, various institutions, fields of study, and sectors use these terms differently or use their own language to describe these or similar concepts. For example, the U.S. Army Corps of Engineers identifies four steps to risk analysis: risk characterization, risk quantification, risk evaluation, and risk management (USACE 1992). While some overlap with the NRC terminology is evident, there are some differences.

Box 8.1 *Risk and Uncertainty*

Risk and uncertainty are typically differentiated on the basis of probability uncertainty, specifically whether or not objectively known probability distributions can be used to describe potential outcomes. In risk situations, they can; in uncertain situations, they cannot. The boundaries between risk and uncertainty are, however, not clear-cut. Risk and uncertainty can be envisioned as intermediary points on a continuum of knowledge from complete certainty to complete ignorance, as shown in the below diagram. The right end of the continuum is comprised of objective risks. Proceeding to the left, probabilities become less statistically sound and gradually merge into subjective probabilities. Finally, at the end of the continuum, no probabilities can be assigned.

Complete Ignorance Uncertainty Risk Complete Certainty

No Probabilities Subjective Probabilities Objective Probabilities

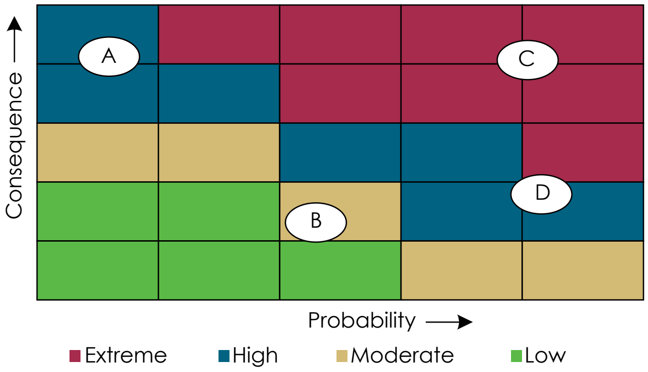
Because these differences in terminology permeate all discussions of risk, establishing some basic terminology is necessary. In the most basic sense, risk itself has two components: a consequence component (the magnitude of harm should the event occur) and a probability component (the likelihood that an adverse event will occur). Risks can quickly be classified along these lines as shown in Figure 8.1. This view of risk has become quite commonplace.

The *consequence* component of risk refers to the magnitude of harm should an adverse event occur. Consequence is a function of both the adverse event itself and the affected system. A tropical cyclone striking an uninhabited area may have little consequence for society. The same storm striking a populated area may have greater consequences.

The *probability* component refers to the likelihood of an adverse event occurring. By convention, the word risk sometimes refers only to this probability component, also known as event risk. We define risk more broadly to include the consequence component. Establishing the probability of an undesirable event can be challenging, especially when conditions are changing (e.g., socioeconomic conditions). Establishing reliable probability estimates under climate change is even harder, and in many cases, impossible.

Figure 8.1 displays probability and consequence of events with similar and different effects. Events A and C have similar consequence. But, event C has higher probability than event A. So, event C would be of greater concern to a risk manager. Event D is as likely to happen as frequently as event C, but has less consequence. So, event D would be of lesser concern. Event B has moderate probability, but relatively low consequence. It would be of less concern than events D and

Figure 8.1 Consequence and probability components of risk



C, which have higher probabilities of occurring and have greater consequence. Whether event B would be of greater concern than event A depends on the relative consequences and probabilities of these two events. In this diagram, event B is considered to be of moderate concern, less than event A, but this is a value judgment. It may be possible that a relatively low probability event such as A may be of higher concern than event D because the consequences of A are quite high or unacceptable (e.g., the probability of an upstream ice dam breaking free and flooding downstream may be extremely low, but the consequences may be unacceptably high, e.g., if flooding will result in loss of many lives and destruction of much property).

Distinctions exist between *exposure*, *sensitivity*, and *adaptive capacity* (e.g., Smit et al., 2001). Exposure is the frequency of a climate event occurring and the magnitude of the event itself (e.g., the likelihood of a Category 3 tropical cyclone striking a coastal area). Exposure is also a function of the location and size of a system that can be affected by the event. Nairobi is not exposed to sea level rise, but Mombasa is. Sensitivity is the extent to which an exposed system will be affected (e.g., a low lying heavily populated coastal area may be very sensitive to a Category 3 tropical cyclone). The Dutch are less sensitive to sea level rise because they have built defenses, while Bangladesh lacks sufficient defenses and is more exposed. Finally, adaptive capacity is the ability of the system to cope or adapt to the event or change in conditions such as change in climate. Developed countries generally have more adaptive capacity than developing countries. The exposure, sensitivity, and adaptive capacity of the affected system are collectively known as *vulnerability*.

In water management, the probability of occurrence of an event of significant consequence (e.g., a flood) often cannot be controlled. However, exposure (e.g., location of critical assets), sensitivity (e.g., hard versus soft infrastructure), and adaptive capacity (e.g., evacuation capability, level of development) are factors that to some degree can be controlled. Because there is often little a water manager can do to decrease the probability of an adverse climate event, water managers must look to policy interventions that reduce exposure of affected systems and sensitivity in order to address most climate-related risks to water investments.

***Top-down* approach to decision making focuses on the probability of an adverse event resulting from climate change.** An attempt is first made to characterize the likelihood that there will be an adverse event. This characterization is often difficult to establish under the best of circumstances due to nonlinearities in the climate and biophysical system, multiple interacting variables, temporal effects, ignorance of confounding variables, and so forth. Nevertheless, an assessment of probability is generally worthwhile as part of a holistic approach to risk-based decision making. In regards to climate change, top-down assessments use the output of computer models to project changes in climate and the consequent impacts on, for example, water systems. Results are used to understand the vulnerability of a system, and adaptations can then be designed to reduce those vulnerabilities.

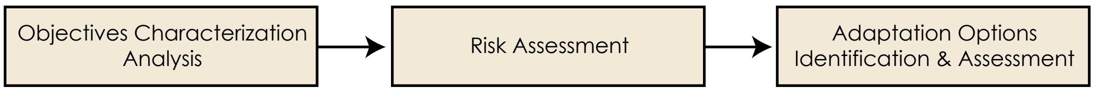
***Bottom-up* decision making involves investigating the exposure, sensitivity, and adaptive capacity of the system of concern.** Water managers often use a bottom up approach in their operational decision making to determine the consequences of an adverse event without getting bogged down in modelling of probabilities resulting from multiple climate models as models of biophysical systems. Assessments of potential damages from a flood event, the flow capacity of storm water systems, or the ability of different water users to sustain a period of water unavailability are all examples of focusing on the consequences and system vulnerability. Again, this is an important element of risk-based decision making and should generally be done in conjunction with identifying system objectives. In regards to climate change, bottom-up assessments look at the affected system instead of climate models. Such assessments determine thresholds at which changes in climate may pose significant consequences in terms of operational, safety, or other concerns. The bottom-up approach starts with knowledge of the project or system, rather than of climate. This can be easier for water managers to apply because they can rely on their knowledge of their water resource systems, rather than trying to master output of climate change models.

Because climate change risk-based decision making is inherently concerned with the future, it must incorporate information about projected changes that may not be reflected in historical records. This entails significant uncertainty both about the probability and the consequence of an adverse event. While the best possible information should be gathered about the probabilities of adverse events, recognizing the limitations of such knowledge allows water managers to consider different types of policy responses to manage the risks, such as those discussed below. Both top-down and bottom-up approaches can be used to identify the change in climate that can increase vulnerability beyond some critical threshold. While top-down assessments are often limited to the outputs of models, development of adaptations typically requires extensive knowledge of a system, that is, a bottom-up approach.

Risk-based decision framework

Risk-based decision making is the systematic consideration of the probabilities, consequences, and values associated with different decision alternatives. Risk-based decision making is the process of choosing among alternative courses of action to achieve a defined objective based upon an assessment of the probability of an adverse event, the vulnerabilities of the system (e.g., the water investment) to that adverse event, and values associated with outcomes (e.g., which risk should most be avoided). There are many risk assessment frameworks in many sectors (Willows and Connell, 2003, Broadleaf and MJA, 2006). A brief review of two frameworks for risk-based assessment of climate change is provided in Annex B. The discussion below is adapted from these two sources and for application to the water sector. In general, risk-based approach involves the following general stages: project objectives definition and characterization of the system components; knowledge of the likelihood and consequences of adverse events that could compromise those objectives; identification of the options for adapting the system or project to render it less vulnerable in the face of the identified risks; and assessment (either quantitatively or qualitatively) of adaptation options. A schematic of the decision framework is given in Figure 8.2. These stages are described below in more details.

Figure 8.2 Stages in risk-based decision making



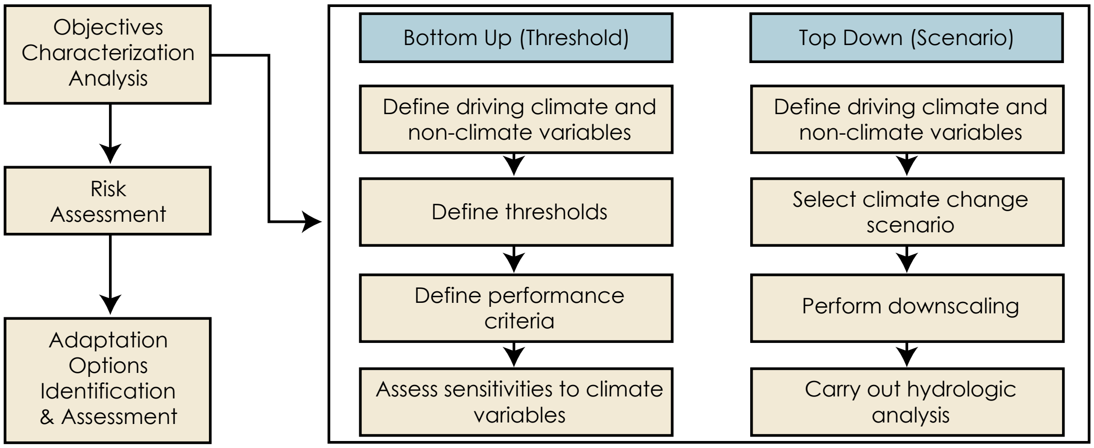
Stage 1 – Identify problem, objectives, performance criteria and rules for decision-making

This initial stage includes the following steps:

1. Define decision problem and objectives—identify exposure units/receptors (i.e., system of interest) and timeframe, establish overall objectives.

2. Establish ‘success’ or ‘performance’ criteria and associated thresholds of tolerable risk. Success criteria are measures (indicators and values) against which adaptation options will eventually be appraised (e.g., effectiveness, flexibility, implementability, economic efficiency, etc.). Criteria may express the risk preference of decision-makers (e.g., system reliability reached 90% of the time). Criteria that are of particular relevance to water systems are reliability, robustness and resilience (discussed in depth later in this chapter). These are sometimes referred to as the ‘threshold-type’ metrics (Stakhiv, 2009) as opposed to ‘absolute’ metrics such as reservoir elevation, in-stream flow minima, electricity generation, or monetary flood damages).
3. Identify rules for decision-making that will be applied to evaluate options (below), also reflecting risk preference of decision-makers. Rules could include cost benefit analysis; cost effectiveness analysis; multi-criteria analysis. Risk preference could include risk aversion, etc. Figure 8.3 shows the template for stage 1.

Figure 8.3 Stage 1 – Objectives identification and system characterization



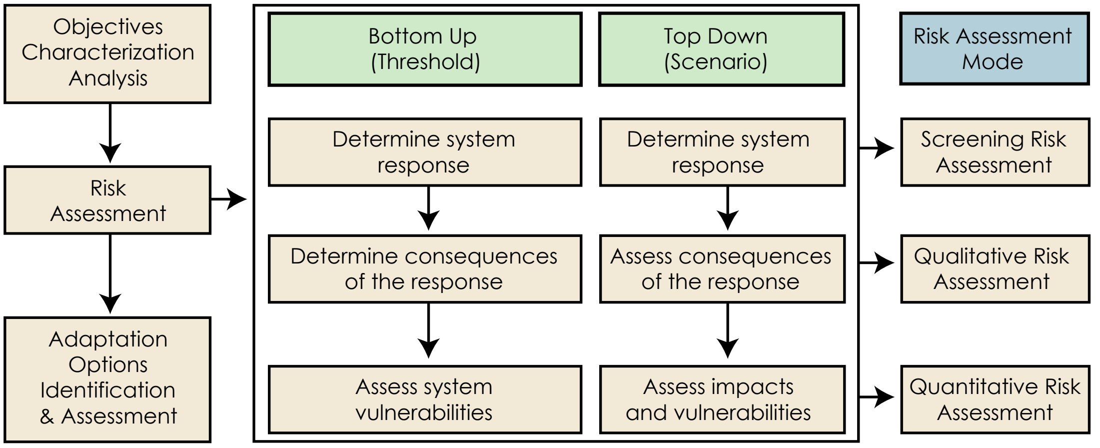
Stage 2 – Assess risks

This stage includes the following steps:

1. Identify the climate and non-climate variables that could influence potential outcomes, i.e., that the exposure unit is potentially sensitive/vulnerable to (e.g. create pathways linking important variables to exposure/units and decision criteria).
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). For climate impacts, identify coping ranges and critical thresholds (biophysical and/or behavioral). Estimate likelihood of impact (quantitatively or qualitatively, as feasible). Prioritize risks and determine extent of uncertainties.

Knowledge of the probability of an adverse event can range from well known (e.g., the likelihood of sea level rise eventually inundating a coastal water treatment facility) to probabilistic (e.g., the variability of streamflows during a rainstorm) to based on expert judgment (e.g., the recurrence period under climate change of what we historically defined as a 100 year flood) to relatively unknown (e.g., the probability of decade-long drought under climate change). The level of uncertainty associated with an adverse event is a significant factor entering into the choice of decision making strategies and tools that a water manager might utilize as discussed below. Figure 8.4 gives the template for stage 2.

Figure 8.4 Stage 2 – Assessment of risks

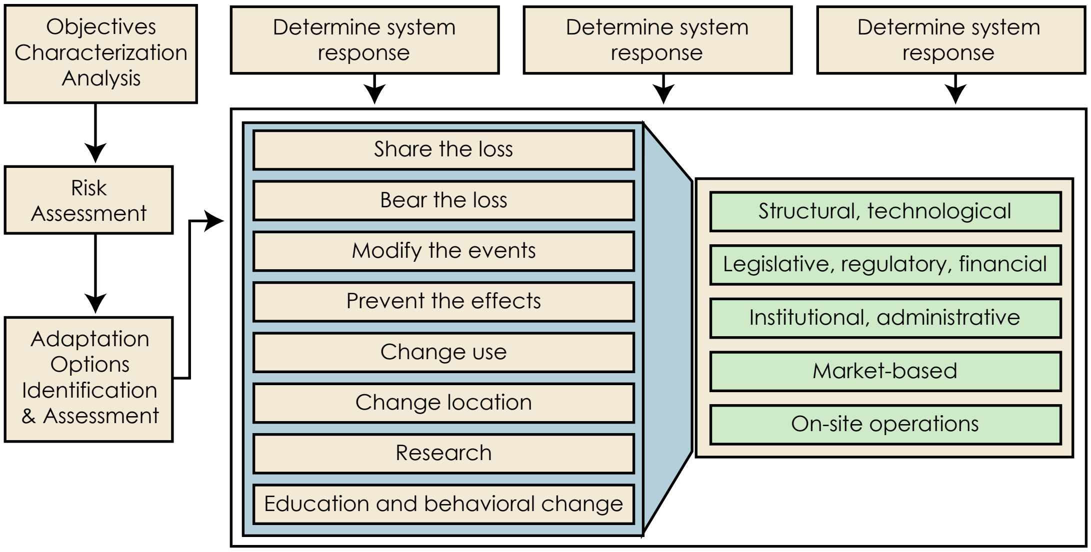


Stage 3 – Identify and evaluate options to manage risk

This stage includes the following steps:

1. Identify (any) potential adaptation options to meet 'success' criteria (and are within thresholds of tolerable risk). A list of adaptation options identified in the review of the Bank's water portfolio is given in Chapter 6. Figure 8.5 shows the template for this stage. A typology of adaptation options adapted from Burton (1996) is imbedded in this template.

Figure 8.5 Stage 3 – Options identification and assessment to reduce risk



2. Evaluate adaptation options according to degree of uncertainty and established rules of decision-making. In all circumstances, look for no regrets, low regrets particularly so when there is high uncertainty. If 'risk' cannot be quantified, can also use approaches for decision-making under 'uncertainty' (Willows and Connell, 2003). The options of 'do nothing' or 'delay decision' are possible. Avoid climate decision errors (over-adaptation, under-adaptation and associated maladaptation).

Considerations for the water sector

Susceptibility of water systems to climate change

A special class of diagnostic indicators identified as threshold-type or dynamic indicators are applied to the analysis of specific water resource systems or system design configurations. Several measures of the robustness of water systems to climate change have been proposed that permit the evaluation of a specific design configuration over a range of system inputs and service levels (Hashimoto et al., 1982a, 1982b). Each indicator is based on the probability that a system, characterized by a given set of design parameters, will provide the intended level of services under a range of dynamic inputs and/or demand conditions. These indicators enable an analysis that extends beyond climatic means to encompass seasonal and interannual variability, serial correlation properties, and the occurrence of extreme events. The measures of system performance are defined over a sequence of discrete time periods. Within each period, the system either performs (provides an acceptable level of services) or fails to do so, which leads to the following complementary metrics.

- ***Reliability*** is how often a system fails according to some defined criteria. It is also defined as the likelihood that services are delivered (no failure) within a given period, expressed as a probability. High probabilities indicate high reliability.
- ***Resiliency*** is how quickly a system recovers from a failure
- ***Robustness in*** a water resources system, this is, conceptually, the extent to which a system design is able to deliver optimal or near-optimal levels of service over a range of demand (input) and supply (resource) conditions. One common definition of robustness emphasizes *flexibility*: the ability of a system to adapt to a wide range of operating conditions through relatively modest and inexpensive levels of redesign, refitting, or reoperation.

Adaptation Options for Water Systems

There are two perspectives from which water management under climate change can be considered. One focuses on potential adaptation options for reducing vulnerability and the other, on the decision-making process under uncertainty. Each of these provides slightly different insights into the question of 'when and how should water managers behave differently'. There is a common thread between the two in highlighting that traditional approaches in many cases suffice, although there are also instances when the 'additional' element of uncertainty arising from climate change will call for innovative responses. A brief description of some indicators used for assessment of vulnerability at the systems level is given in Box 8.2.

Potential options for adapting to climate change and variability in the water sector can be categorized into those that carry 'no regrets' and those that are 'climate justified'. Many of the options to reduce vulnerability to climate variability are no different in a world with climate change than they are in a world without. These include demand management measures

Box 8.2 Standardized indicators to assess the vulnerability of regions and systems to climate change

Standardized indicators can help identify regional patterns of water sector vulnerability to changes in climate and hydrology. Using indicators to diagnose the vulnerability of water systems increases the insight of water managers into how climate change may affect the functioning of infrastructure design and the efficacy of alternative management practices, and can be used proactively to diagnose vulnerability before planning, financing, and implementing a water project. Vulnerability to climate change with respect to water systems is strongly related to three factors:

- ***Climate and hydrology***: the status of regional water resources – mean, trends, and variability in usable supplies;
- ***Water demand, use, and depletion***: the level, structure and timing of abstractive and consumptive demand for water, including groundwater.
- ***Water storage and management infrastructure***, which mediate between hydro-climatic conditions and societal demand by regulating water availability in space and time.

Indicators can be used to quantify each factor discretely, or to examine the overlay of supply, demand and management infrastructure within a given region. One example of a supply-related indicator is the ***runoff ratio***, defined as the percentage of annual precipitation converted to surface runoff and renewable groundwater recharge. Low values of the runoff ratio are associated with high vulnerability, since modest changes in temperature or precipitation can lead to large relative changes in available water supplies.

Water demand vulnerability indicators place emphasis on demand relative to available supply, since the extent of unused capacity provides the buffer between uncertain future supply and demand conditions. One indicator is ***water crowding***, defined as the number of people per million cubic meters of water per year (Vörösmarty et al., 2005). A crowding index greater than 1,000 indicates potential scarcity. A closely related indicator is the ratio of annual withdrawals to renewable water supply, identified as ***relative water demand*** (Vörösmarty et al., 2000). These concepts have been extended to ***water use regimes***. This two-dimensional indicator distinguishes between (i) *undeveloped* or natural flow-dominated, (ii) human flow dominated, (iii) *depleted* or withdrawal dominated, and (iv) *surcharged*, or return-flow dominated regimes.

The extent to which water storage and management infrastructure provides a buffer for societies facing climatic variability or change is an important component of vulnerability and resilience. A simple indicator is the ***storage-to-flow ratio***, defined as the ratio of total basin storage capacity to annual renewable discharge. A special class of infrastructure-related indicators can also be used to diagnose the vulnerability of specific water resource systems or system design configurations to alterations in supply and/or demand conditions. They are identified as ***reliability*** (how often a system fails), ***resiliency*** (how quickly a system recovers from a failure), ***vulnerability*** (how significant are the consequences of a failure), and ***robustness*** (how well a system performs over a range of conditions). These indicators are described in Hashimoto et al. (1982a, 1982b).

to increase water use efficiency and productivity, such as water-conserving irrigation technologies; wastewater recycling; economic incentives, including water pricing; and the encouragement of water markets that move water to high-valued uses. They also include, for example, measures to improve early warning systems and risk-spreading (e.g., disaster insurance). These options carry '*no regrets*' in that they would go a long way in confronting the climate change challenge, yet they are often justifiable even under current conditions of variability. On the other hand, other actions might be justifiable under significant change in climatic variability. '*Climate justified*' actions include, for example, constructing new infrastructure (dams, underground storage, irrigation systems), retro-fitting existing infrastructure, changing rules of operation, tapping new sources of water (e.g., desalinization), water transfers, conjunctive use of surface and groundwater, innovative demand management, etc.

The distinction between 'no regrets' and 'climate-change justified' options is important in near-term and long-term decision making. For "no regrets" options, uncertainties in climate projections are to a large extent immaterial. By definition, these actions should be taken in order to meet current economic, social and environmental objectives, but they also serve the dual purpose of reducing vulnerabilities to future climatic conditions. It is in the realm of the 'climate-justified' that water managers will have to make difficult decisions about how to balance the political, economic, social and environmental costs of action versus of non-action, given an uncertain future. They will have to seek and apply new technologies and management methods to ensure that system ***reliability*** is maintained under changing climate circumstances. They will have to shift their thinking on how to plan and design more ***resilient*** water interventions. And, they will need to develop ***'intelligent systems'*** that are ***robust*** in the sense that they are able to deliver (near) optimal levels of service or management over a range of conditions, including through relatively modest re-design, retrofitting or re-operation. Implicit in robustness is also ***flexibility***, that is, the ability to anticipate and react to a wider and largely unknown range of future climatic conditions. All of these actions will require use of a variety of new and innovative tools in the areas of economics, finance, institutions, infrastructure and technology.

Categories of adaptation options

One of the most operational and often-used classifications of adaptations was introduced in the Intergovernmental Panel on Climate Change's (IPCC's) Third Assessment Report, based on Burton, et al. (1996). Below is an updated list, revised for focus on the water sector.

- *No action*. All adaptation measures may be compared with the baseline response of "doing nothing" and accepting the economic, social, environmental, or other losses caused by the impacts of a changing climate. In addition to providing a baseline for comparison, "no action" occurs where the costs of adaptation are considered too high relative to benefits, when information about risks is lacking, and where political will does not coalesce to address adaptation, among other situations.
- *Insurance*. Many communities face some risk of high consequence climate events, such as hurricanes, floods, tornadoes, wildfires, and so forth. One way to hedge against these risks is by sharing the losses among a wider community. Private or public insurance mechanisms can share risks by raising revenues from a large insured pool to provide coverage for relief and reconstruction. Insurance includes mechanisms such as private insurance policies, public insurance programs, and public or institutional relief efforts, but it also includes a variety of less formal mechanisms such as reliance on church and non-governmental organization relief efforts. Insurance is typically used to compensate victims for losses and the compensation is typically used to repair or rebuild damaged structures or compensate for losses that cannot be repaired or rebuilt. Note that when insurance regulations or policies promote an increase in vulnerability to climate events, insurance acts instead as a form of maladaptation. Correcting such maladaptations can go a long way toward reducing vulnerability and protecting people, their property, and their environment from climate risks. Governments can also serve to share loss by providing financial and other aid following disasters. Government funds can be used to rebuild destroyed property or compensate victims for losses. This tends to be more feasible in

larger countries (where it is more likely that an adverse event only strikes a small portion of the country's land mass) and wealthier countries which have more financial resources to devote to insurance.

- *Engineered protection.* For some climate impacts, it is possible to engineer protective measures that reduce the risks or consequences of the impact. Examples include flood control works (e.g., dams, dikes, levees, sea walls), creating fire breaks near the built environment to reduce fire hazard, and building new or improved water storage facilities to hedge against drought. One of the challenges of engineering adaptations to climate change is the uncertainty about the magnitude of change in variables for which even the direction of change is unknown, e.g., uncertainty the magnitude of temperature increase, sea level rise, or increase in intense precipitation.
- *Managing the risk.* A frequently used set of adaptation measures involves steps to manage the effects of climate change. Examples include improved warning systems and evacuation centers for flood or cyclones, and diversifying a community's water supply portfolio to increase resilience to drought. Other examples might include limiting development in vulnerable areas or promoting water efficiency measures to reduce demand for water and vulnerability to droughts.
- *Change use.* Where the threat of climate change makes the continuation of a climate sensitive activity too risky, consideration can be given to changing its use. Governments and institutions can play an important role in this adaptation option, for example, by regularly revising flood zones based on projections of altered precipitation regimes or sea level rise. As a result, lands once slated for development may be better suited as buffers for floods or natural floodplain migration. Government subsidies, regulations, taxes, and other incentives can play a large role in facilitating or impeding this adaptation option. For example, subsidies for specific crops may provide an economic disincentive for farmers to change from water sensitive crops to drought tolerant ones in areas where such a changed use makes sense.
- *Change location.* In many instances the location of physical infrastructure or climate sensitive activities is the primary source of vulnerability to the impacts of climate change. For example, buildings in floodplains or along the coasts will face increasing vulnerability to floods and coastal storms; water intensive crops grown in arid environments may require more water than can be reliably delivered to those locations in places where drought frequency increases; and some fisheries may migrate northward to cooler waters. Settlements or economic activities may need to be relocated in response to such changes. This adaptation can carry significant to extremely high costs, but may be the unavoidable adaptation of last resort. The need to abandon some areas has been advocated by many, including Sachs (2008).
- *Research*. For many adaptations, improved understanding of climate change and its impacts is needed. More geographically and temporally precise climate projections can aid adaptation as it could reduce uncertainties about the direction and magnitude of change in key climate variables such as precipitation. Many potential impacts of climate change are inadequately understood. Adaptation itself is not well understood, particularly how individuals and societies will respond to changing climate. This is not an option for individual water managers, but the need for research needs to be communicated to the research community.
- *Education and behavioral change*. Another type of adaptation focuses on changing the practices of individuals or institutions. This often involves the dissemination of knowledge through education and public information campaigns. One example is waste of water, for example, by leaving taps on or not attending to leaks. Changing behavior can be fostered through education campaigns, appropriate regulatory instruments, pricing, incentives, taxes, and subsidies or the removal of such instruments if they impede adaptation.

Class of projects for which risk-based analysis would be particularly essential

Climate change will affect most water systems to some degree. However, some water services or resources by their very nature are more vulnerable to climate change than others. For example, small or distributed water supply systems that can easily make incremental changes at low cost are vulnerable to climate change, but may face less exposure to changes in climate, may be less sensitive to climate changes, or may have sufficient adaptive capacity to manage those changes. The systems below, however, are particularly vulnerable and special care should be taken to flag such water investments for risk-based decision making. These systems would likely be designed differently if climate change were taken into account, and failing to do so would likely cause significant economic loss (Hobbs, et al 1997).

- *Highly capitalized or unique projects*: Any project that requires a very large investment or has a high opportunity costs, such as most infrastructure systems or large watershed protection projects, needs to include consideration of climate change because the stakes of failing to accurately assess risk are simply too high, often on the order of many millions of dollars.
- *Engineering structures with long lifetimes*: Water infrastructure projects often have lifetimes of 50 years or more. The best available science indicates that climate changes may not be significant for planning purposes over just a few years, but over the course of many decades, changes in climate are expected to manifest in ways significant for planning purposes.
- *Multi-purpose infrastructure systems*: Some systems serve multiple purposes, such as dams that provide water supply storage and flood control. The management of such systems often involves tradeoffs between these purposes (e.g., how much water to keep in a reservoir is driven in part by ensuring enough additional capacity to capture flood waters should a flood occur). Because these systems must balance risk related to multiple purposes, it increases the importance of incorporating climate change considerations.
- *Long-lived benefits and costs*: Similarly, any project whose benefits or costs are spread out over a long timeframe may need to incorporate potential future changes in climate to see how it affects those benefits or costs. This could radically alter the justifiability of a water project.
- *Systems susceptible to climate anomalies or extreme events*: Any water investment or management regime that can be significantly affected by floods, droughts, hurricanes, or other climate anomalies needs to consider the potential increase in risks from climate change because these extreme events account for the bulk of climate-related damages to water projects. Small increases in the frequency or severity of these events can lead to exponential increases in damages.
- *Urban water supply*: Urban water demand is increasing in most places, but it can be managed on both the demand and the supply side. Because of the multiple adaptation possibilities (e.g., leak reduction, metering, eliminating unauthorized taps), urban water supply provides an excellent opportunity to relieve stress on basin-wide water systems and thus makes the entire system less vulnerable.
- *Water systems facing non-climate stress*: Many water systems are vulnerable to non-climatic trends such as urbanization, deforestation, changes in agricultural or industrial water demands, and so on. Because these water systems become more stressed, they also become more vulnerable to changes in hydrology and hence climate change.

Identification of water systems or projects that merit consideration of risk-based decision making involve a two step process. First we recognize the need to incorporate risks of future events into our planning decisions. Next we must figure out what kinds of remedial action can be taken to reduce those risks, and what the costs and benefits of those risk management options may be. The term adaptation refers to policy actions intended to reduce the vulnerability of systems to climate variability and change.

Assessing risk: application to multi-purpose infrastructure projects[26]

Depending on the class of project and the expected risk and consequences of exposure to climate change, the level of analysis varies. As an illustration of the application of the risk-based decision making, the process for assessment of risk associated with multi-purpose infrastructure is presented here. This multi-purpose example focuses on elements of stages 2 and 3 of the risk-based assessment framework described above.

Hydrologic drivers for multi-purpose hydraulic infrastructure

The primary driver of climate change impacts on dams and reservoirs is temperature. Current climate models suggest that the effects of temperature increases are felt throughout the climatic regime, leading to hydrologic changes (e.g., seasonal redistribution and duration of rainfall) and other related impacts. These hydrologic changes are manifested as periods of increased rainfall or floods, as well as periods of reduced rainfall or drought. In addition to precipitation effects, increased temperatures are impacting glacier and snowmelt patterns, while also creating more extreme hurricane or typhoon conditions with associated high winds. A representative list of temperature, rainfall, and wind related effects that may impact a multipurpose hydraulic infrastructure is provided in Box 8.3.

While acknowledging the myriad effects on multi-purpose infrastructures from all of the above drivers, this assessment of climate change impacts is focused on the primary hydrologic drivers of vulnerability as described earlier in this report:

- Annual Average Precipitation;
- Precipitation Extremes;
- Glaciers and Snow;
- Sea Level;
- Evapotranspiration;
- Soil Moisture;
- Runoff and River Discharge.

Project components

The project components are first described and assessed in terms of their sensitivity to the major hydrologic climate change drivers. The risk-based analysis framework is then developed in a matrix format to characterize the severity or sensitivity of climate change impacts on each component. The analysis framework is then applied, using a defined methodology for evaluation and scoring of impacts, to obtain an overall picture of project vulnerability to climate change.

- Dam Structure;
- Reservoir Storage;

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[26] This methodology is described in more detail in the background report Water and Climate Change: Assessment of Climate Change Impacts on Multipurpose Infrastructure

Box 8.3 Potential impact some of key hydrologic drivers

Temperature

- Increased mean ambient temperatures;
- Increased peak temperatures;
- Increased evaporation;
- Increased humidity (if accompanied by a generally wetter climate);
- Increased snowmelt and retreating of glaciers;
- Increased vegetation (if accompanied by generally higher rainfall);
- Loss of vegetation (if accompanied by periods of prolonged drought);
- Increased desiccation (if accompanied by periods of prolonged drought);
- Increased insect populations;
- Increased methane production in reservoirs from rotting vegetation; and
- Increased stratification and water quality variations in reservoirs.

Rainfall

- Increased peak runoff and river discharge;
- Increased reservoir yields (in the case of prolonged wetter conditions);
- Reduced reservoir yields (in case of prolonged drought periods);
- Higher river floods;
- Higher localized storm intensities;
- Increased vegetation (in case of prolonged wetter conditions);
- Increased sediment (in the case of prolonged drought periods that can desiccate watershed soils);
- Increased debris flows;
- Increased lightning incidents (in the case of high energy storms); and
- Prolonged solar exposure (in the case of prolonged, reduced cloud cover).

Wind

- Increased prolonged wind speeds;
- Associated increases in the wave heights on reservoirs;
- Associated increased "seiche" (wind set-up) effects on reservoirs;
- Increased gust speeds;
- Associated increased structural wind loading on exposed structures;
- Greater amounts of atmospheric dust; and
- Greater amounts of windblown debris.

- Service & Auxiliary Spillways;
- Intake Works;
- Hydropower Plants;
- Low-Level Outlet Works;
- Tunnels;
- Open Channels.

In order to prioritize and justify design accommodations to adapt to climate change, it is desirable to have a logical, repeatable methodology. This is particularly important for quantifying the risks related to the various dam and reservoir project components exposed to climate change drivers, and then determining the most attractive adaptation strategies for implementation. For a given exposure, the risks are identified as a function of criticality, sensitivity and adaptability of each component.

A risk-based approach to evaluating the sensitivity of multi-purpose infrastructure components to climate change begins with assessing the risk factors (or attributes) that are important to defining the component's response to a climate-change induced stressor. These risk attributes can be organized in three indicative categories as follows:

Criticality
- Likelihood of Failure
- Consequence of Failure

Sensitivity
- Robustness
- Resilience

Adaptability
- Adaptive Capacity
- Cost of Adaptation

Mapping the climate change impact onto project components

The component risk analysis starts with mapping the project components to their primary climate change impact drivers. In order to frame the criticality of a given component, the major drivers of climate change impacts on multi-purpose infrastructures are mapped against the principal structural components of the project.

While the matrix on Table 8.1 indicates that there are multiple drivers acting upon a given component, a methodology for identifying the "alpha" driver that governs the design or configuration of the component is needed. To do so, it is necessary to delve more deeply into these relationships in order to assess the vulnerability of the components to climate change impacts. This component assessment represents an essential initial step in ultimately making valid recommendations for adaptive measures to manage, reduce, or eliminate these impacts.

Scoring of component risk

Each component is scored according to the risk attribute within each indicator category. An example of the scoring range and scale is given in Table 8.2.

Each major project component is scored for each indicator. This results in a ranking in each category for each component. This assessment can first be done on a generic basis, using expert knowledge of the planning and design process for a dam or reservoir project. It is then further refined and quantified for a particular project, as further study and available information warrant. The scoring process involves three basic steps:

- Assess and score criticality, vulnerability, and adaptability of the component;
- Apply weighting factor in each category in order to reflect the relative importance of the category in the decision process; and
- Prioritize components on which to focus based on the highest-to-lowest scores obtained.

Table 8.1 Matrix of hydrologic drivers and infrastructure components

Driver of Impact	Dam Structure	Reservoir Storage	Service & Auxiliary Spillways	Intake Works	Hydropower Plants	Low-Level Outlet Works	Tunnels	Open Channel
Average Annual Precipitation (AP)		X		X	X	X	X	X
Precipitation Extremes (EP)	X	X	X	X	X	X	X	X
Glaciers and Snow (GS)	X	X	X	X	X	X	X	X
Sea Level (SL)								
Evapotranspiration (ET)		X						X
Soil Moisture (SM)	X	X	X					
Runoff and River Discharge (RR)	X	X	X	X	X	X	X	X

Table 8.2 Scoring by category for each component

Indicator Category	***Key to Scoring (based on 10 point scale)****	***Weight***
Criticality	Likelihood of Failure Low = 1; Med = 3; High = 5	1*
	Consequence of Failure: Low (affects reliability/availability) = 1; Med (affects performance) = 3; High (affects safety) = 5	
Sensitivity	Robustness**: Low = 5; Med = 3; High = 1	1*
	Resilience**: Low = 5; Med = 3; High = 1	
	Adaptive Capacity (Planned Projects)**: Low = 5; Med = 3; High = 1	1*
Adaptability	Adaptive Capacity (Existing Projects): Low = 1; Med = 3; High = 5	
	Cost of Adaptation (Planned Projects): Low = 1; Med = 3; High = 5	
	Cost of Adaptation (Existing Projects)**: Low = 5; Med = 3; High = 5	

* Scoring scale and weight may be varied as needed.

** Score is inversely proportional to the attribute. The highest total score is assigned to the project component that as the highest criticality, highest vulnerability (i.e., least robust and resilient), and lowest adaptability (i.e., low adaptive capacity and highest cost of adaptation).

For a given project analysis, the scoring for the risk attributes in each category should be done on a consistent and replicable basis that does not introduce a bias into the analysis. The weighting factors, on the other hand, should be varied to test the sensitivity of the category weights on the prioritization of the actions. The dam and reservoir project component risk analysis enables means to identify the project features that are the most sensitive to climate-induced changes in hydrologic conditions. The following sequence for application of the assessment framework defines a methodology for evaluating the impacts of climate change on multi-purpose infrastructures on a logical, replicable basis.

Assessment of project components most at risk

The results of the scoring exercise provide information on the components which are most critical, most sensitive, and least adaptable as priority components for early attention in the planning and design stages of a proposed project. Analysis of existing and future projects differ in that there is more opportunity for planning and designing against vulnerabilities and providing means of adaptation, than for existing projects. Table 8.3 provides a generic matrix template for assessment and ranking for multi-purpose infrastructure projects. Opportunities and strategies for adaptation of multi-purpose infrastructure components to climate change is outlined in Annex C.

Table 8.3 Scoring matrix template

Component	***Criticality Score***	***Sensitivity Score***	***Adaptability Score***	***Total Score***	***Priority***
Dam Structure					
Reservoir Storage					
Spillways					
Intake Works		Enter score for each component and under each category. Sum scores and rank. *Caution*: to be used to gain insight and in conjunction with non-numerical assessments.			
Hydropower Plants					
Low Level Outlet Works					
Tunnels					
Open Channels					
Top Component in Category					

CHAPTER 9:
NEXT STEPS: AN AGENDA ON CLIMATE CHANGE FOR THE WATER PRACTICE

Insight into the various dimensions of water and climate change has identified the gaps and guides the next steps. As the World Bank water agenda mainstreams adaptation to the impact of climate change, the questions raised at the beginning of this report continue to remain valid and should be an integral part of the ongoing work at the water anchor in support of the regions. These questions are: (i) what are the impacts of climate variability and change on water systems, both natural and engineered; (ii) what are adaptation strategies to reduce vulnerability of water systems to these impacts; and (iii) how can the Bank assist client countries in making informed decisions regarding adaptation options in their water investments? In relation to the latter question, it is obvious that factors other than climate change also exert pressure on water resources. In some cases these factors may dominate climate change, in other cases climate change induced pressure may dominate. In all cases, informed decisions regarding water investments have to take into account both the climate and the non-climate induced pressures.

Below the report briefly describes how this flagship effort has provided tools to make better informed decisions regarding water investments and the proposed areas of activity to be carried out in the future by the water anchor in support of the regions to provide a basis for continuous improvements in decision making in conjunction with the continuous expansion of information and knowledge available about the effects of climate change.

Continue to strengthen the analytical foundation

Improve the hydrologic projections and exposure assessment methodology for application in project preparation. A critical step in the Bank's effort in addressing climate change adaptation is an agreed set of future climate change scenarios for each region to ensure consistency and compatibility across work in all sectors. This flagship effort has provided projections of the hydrologic drivers for water investment. Hydrologic variability and climate change signals have been translated to indicators with quantitative measures of magnitude and variability. The next step would be to make them readily available to the regional staff for use. This will require additional analysis of the projections, as well as development of a user interface (or adoption of an existing one) to facilitate use. At the same time, a plan shall be made for updating the projections of hydrologic drivers (and their indicators with quantitative measures of magnitude and variability) for water investments on a regular basis (say every 2 to 3 years) as improved and additional climate change scenarios become available.

Improve the procedure for risk-based approach to adaptation options assessment and decision making. Most conventional interventions in the water sector are not likely to be effective under increased conditions of variability and uncertainty because they have been predicated on the assumption of hydrologic stationarity. The flagship report has considered the issue: how to deal with projections in a world where "stationarity is dead". The report strongly argues for the necessity for incorporation of a formal risk-based approach in water investments. A framework for risk-based analysis is proposed in the report together with an example of how such a framework may be applied to the Bank's project cycle. The next step would be to further expand and formalize this process to allow for explicit characterization of risks, options, and management of risks. The approach should incorporate unfolding uncertainties over time, and account for the performance of adaptation options. This requires increased capability to understand, to quantify, and manage risk in an environment of increased uncertainty.

Improve decision making by expanding economic considerations to explicitly include climate change. The main focus of this flagship effort was to understand and characterize the behavior of the hydrologic drivers that can impact design and operation of various water systems and investments. The current work sets the stage for and provides the needed information for a risk-based approach to the assessment of the economics of water investment.

In any investment decision, economics figure prominently. Two future areas of work are suggested:

1. It is proposed at the country, river basin or even sub-river basin level to prepare assessments of the cost of adaptation. Different interventions will have different costs and in order to focus on cost-effective interventions early in the project cycle it will be valuable to have an assessment of the cost of adaptation to address climate change induce and non-climate change induced water—related risks (whether flooding, water scarcity or other). Work is already under way to assess marginal cost curves for alleviation of water scarcity. Similar, but country or water basin specific work, which also considers the effects of pricing and other institutional policies, may contribute to focus on cost-effective interventions and may provide very useful guidance for DPL type interventions. The division of responsibilities between the Water Anchor's role to provide methodological guidance and the responsibilities of the Bank's regions and country offices for implementation need careful consideration in designing such work.
2. It is proposed to initiate review of the current methodology for project economic analysis and develop methodology for incorporation of climate change impacts at the project level. Specific areas of focus would be i) economic valuations and other metrics for ranking the potential impacts of climate change, and ii) approaches to comparison of costs and benefits over time, risk attitudes, and distributional concerns.

Finally, in the future work is needed on the impact of climate change on social and economic development. Recognizing that climate change has real effects on people's livelihoods, recognizing that these effects make themselves felt mainly via the water cycle, and recognizing that by analyzing the cumulative and cross-sectoral impacts it is possible to gain an understanding of where the Bank may most cost-effectively support countries in their own efforts to improve the livelihoods of poor people, work has been proposed (for example by the China country office) to study the impact of climate change on social and economic development at the country level. It would be useful to expand such work to many Bank client countries and the Water Anchor may contribute by providing back ground material including but not limited to typologies of countries and check lists of impacts and dynamics to be considered.

Incorporate hydrologic variability and climate resiliency considerations in Bank operations

Guidelines for incorporation of hydrologic variability and climate change in project preparation. This would include use of the improved methodology above to broadening the risk-based framework to include all water systems. A related useful product would be a response matrix of the appropriate coping/adaptation strategies to the hydrologic projections by water system, usage and by climate-sub-region. Development of a systematic process for incorporation of response matrix in the project cycle would help streamline the work of task managers. A series of case studies to illustrate the process would also be useful.

Develop practitioners notes for feasibility studies, planning and design studies for infrastructure projects. These notes should address planning and design issues within a basin-wide context, rather than as individual projects. This would help with optimization of infrastructure design for water storage, supply, or hydropower taking into account climate change factors. The case studies carried out as part of the Flagship study can be beneficial in this regard. A note on methodology for evaluating projects on a component (or water system) level, for criticality to project function, vulnerability to climate change impacts, and adaptability in the face of climate change, could be helpful to task managers.

Implications of climate change in managing ecosystems. The objective of this activity would be to first better understand the climate change impacts on aquatic ecosystem functions and resiliency and incorporate a structured approach for factoring them into integrated water resources planning, design, and operation decisions.

The guideline developed for this purpose should address both environmental flow and water quality implications of climate change. It will review how ecosystem services will be affected by the changes in flow volumes, timing and quality due to both natural climate variability and climate change. The implications of altered demand for agriculture, municipal and industrial supply due to climate change on environmental services should be discussed. The various impacts of climate change on water quality in rivers (e.g., sediment loads), lakes and reservoirs (e.g., temperature, dissolved oxygen, mixing, stratification) and groundwater (e.g., saltwater intrusion in coastal aquifers) and their implications on magnifying pollution impacts, including on human health and ecosystem health should be defined. Ecosystem implications of adaptation responses including supply side options and demand management, including reoperations should be described.

Water and carbon footprint of water investments. As part of project planning and implementation, an analysis of the carbon and water footprint of intervention could provide insight into the sustainability of the proposed action.

Strengthen Bank expertise on water and climate change

Bank staff experience and expertise. Climate change has become a major area of focus at the Bank, drawing a great deal of attention at the corporate and the regional levels. Many water professionals are engaged in climate change work as evidenced by the increasing volume of climate-related lending and non-lending activities, as well as seminars, workshops, and briefings to management. With some exceptions, most of the Bank water staff lack practical experience in climate change and hydrologic variability related to water resources management and water services delivery systems. Much of the current expertise, information and data related to the impact of climate change and adaptation strategies exist outside of the Bank. For the Bank to position itself at the forefront of climate change work in the water sector, it is proposed that in-house expertise be strengthened and to the degree appropriate, complemented by external expertise through easily accessible mechanisms. The following specific actions are suggested as a starting point.

- Expand the external technical team of experts and high-level advisory group beyond hydrologic drivers to include economics, and environmental/social aspects of water and climate change.

- Formalize partnerships with leading international, academic, and research organizations that are reputable in the field of climate change in the water sector.
- Develop and implement programs for building capacity based on assessment of the knowledge and experience of Bank staff and identified gaps.
- Engage the newly established Water Resources Management Thematic Group to investigate the operational implications of incorporating climate change adaptation options in water investments.

10. REFERENCES

Alcamo, J. and T. Henrichs. 2002. Critical regions: A model-based estimation of world water resources sensitive to global changes. Aquatic Sciences 64: 352–362.

Arnell, N.W. 2003. Effects of IPCC SRES emissions scenarios on river runoff: A global perspective. *Hydrology and Earth System Sciences* 7(5): 619–641.

Arnell, N.W. 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Environmental Change*.14: 31–52.

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, IPCC Secretariat, Geneva, 210 pp.

Berry, P., Paterson, J., Cabeza, M. et al. 2008. Mitigation measures and adaptation measures and their impacts on biodiversity. Minimisation of and Adaptation to Climate change: Impacts on BiodiverSity (MACIS). Oxford University, 320pp.

Bramer, D. Wojtowicz, D., Hall, S. (2008): University of Illinois WW2010 Project. (Available from: *http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/hyd/smry.rxml)*.

Broadleaf and MJA. 2006. Climate Change Impacts & Risk Management: A Guide for Business and Government. Broadleaf Capital International and Marsden Jacob Associates. Australian Greenhouse Office, Department of the Environment and Heritage, Canberra AGO, pp. 19–21.

Burton, I. 1996. "The Growth of Adaptation Capacity: Practice and Policy." In: J.B. Smith, N. Bhatti, G. Menzhulin, R. Benioff, M. Budyko, M. Campos, B. Jallow, and F. Rijsberman (eds.). Adapting to Climate Change: Assessments and Issues. New York: Springer. pp. 55–67.

Döll, P., and M. Florke. 2005. Global-scale estimation of diffuse groundwater recharge. Frankfurt Hydrology Paper 3. Institute of Physical Geography. Frankfurt University, Frankfurt.

Döll, P. 2009. Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. Environ. Res. Lett., 4, 036006 (12pp).

Frederick, K., D. Major, and E. Stakhiv. 1997. Water Resources Planning Principles and Evaluation Criteria for Climate Change: Summary and Conclusions. *Climatic Change* 37: 291–313.

Giannini A., M. Biasutti, I. M. Held, and A. H. Sobel. 2008. A global perspective on African climate. Climatic Change 90 (4): 359-383.

Hashimoto, T., D.P. Loucks, and J.R. Stedinger. 1982a. Robustness of water resources systems. *Water Resources Research* 18(1): 21–26.

Hashimoto, T., J.R. Stedinger, and D.P. Loucks. 1982b. Reliability, resiliency and vulnerability criteria for water resource system performance evaluation. *Water Resources Research* 18(1):14–20.

Hazen, A. 1914. Storage to be provided in impounded reservoirs for municipal water supply. *Trans. ASCE* 77:1539–1640.

Hobbs, B.F., P.T. Chao, and B.N. Venkatesh. 1997. Using Decision Analysis to Include Climate Change in Water Resources Decision Making. *Climatic Change* 37: 177–202.

IGRAC. 2004. Degree of Groundwater Development. Map provided on the Global Groundwater Information System. Available online: http://igrac.nitg.tno.nl/ggis_map/start.html.

IPCC. 2001. Climate Change 2001: The Scientific Basis, J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, D. Xiaosu, and K. Maskell (eds.). Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA.

IPCC. 2007a. Summary for policymakers. In Climate Change 2007: The Physical Science Basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B.

Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, UK and New York, USA.

IPCC. 2007b. 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 [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC. 2007c. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kabat, P., Van Schaik, H., Appleton, B. 2003. Climate Changes the Water Rules: How Water Managers Can Cope with Today's Climate Variability and Tomorrow's Climate Change. Dialogue on Water and Climate. The Netherlands.

Kirshen, P., M. McCluskey, R. Vogel, and K. Strzepek. 2005. Global analysis of changes in water supply yields and cost under climate change: A case study in China. *Climatic Change* 68: 303–330.

Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, P. Kabat, B. Jiménez, K.A. Miller, T. Oki, Z. Sen and I.A. Shiklomanov, 2007: Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 173–210.

McMichael, A. J. and A. Haines, 1997. Global climate change: the potential effects on health BMJ 315: 805–809.

Milly, P.C.D., K.A. Dunne and A.V. Vecchia. 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature 438(17): 347–350.

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer. 2008. *Science* 319: 573–574.

Mogaka, H, S. Gichere, R. Davis and R. Hirji. 2006. Climate Variability and Water Resources Degradation in Kenya. World Bank Working Paper No. 69. World Bank: Washington, DC.

NRC. 1983. Risk Assessment in the Federal Government: Managing the Process. U.S. National Research Council. U.S. Government Printing Office, Washington, DC.

NRC. 1994. Science and Judgment in Risk Management. U.S. National Research Council. U.S. Government Printing Office, Washington, DC.

Raskin, P., P. Gleick., P. Kirshen, G. Pontius, and K. Strzepek. 1997. *Water Futures: Assessment of Long-Range Patterns and Problems, Comprehensive Assessment of Freshwater Resources of the World*. Stockholm Environment Institute, Stockholm.

Sachs, J. 2008. Commonwealth: Economics for a Crowded Planet. Penguin Press.

Smakhtin, V., C. Revenge, P. Doll, and R. Tharme. 2003. *Putting the Water Requirements of freshwater into the Global Picture of Water Resources Assessment*. IWMI, Colombo.

Smit, B., Pilifosova, O., Burton, I., Challenger, B., Huq, S., Klein, R.J.T. and Yohe, G. 2001. Chapter 18 Adaptation to climate change in the context of sustainable development and equity. IPCC Third Assessment Report, Intergovernmental Panel on Climate Change.

Stakhiv, E., and R. Pietrowsky, 2009. Adapting to climate change in water resources and water services. Institute for Water Resources, U.S. Army Corps of Engineers. Presented at Fifth World Water Forum, Istanbul, March 2009.

Stern, Sir Nicholas. 2006. *The Economics of Climate Change: The Stern Review*. HM Treasury. London.

Strzepek, K, R. Balaji, H., Rajaram and J. Strzepek 2008. A Water Balance Model for Climate Impact Analysis of Runoff with emphasis on Extreme Events, In preparation

Sullivan C.A. and J. R. Meigh. 2005. Targeting attention on local vulnerabilities using an integrated indicator approach: the example of the Climate Vulnerability Index. Water Science and Technology, Special Issue on Climate Change 51 (5): 69–78.

Sullivan, C.A. and C. Huntingford. 2009. Water Resources, Climate Change and Human Vulnerability Proceedings of the MODSIM Conference, Cairns, July 2009.

Tehelka. 2008. Climate Change: What Men Can Do?, 3 May 2008.

Trenberth, K. E., A. Dai, R. M Rasmussen, and D. B. Parsons. 2003. The Changing Character of Precipitation. Bulletin of the American Meteorological Society. 84: 1205–1217.

UN. 1996. *Indicators of Sustainable Development Framework and Methodology*. United Nations Division for Sustainable Development, New York.

USACE (US Army Corps of Engineers). 1992. Guidelines for Risk and Uncertainty Analysis in Water Resources Planning, Vol 1 – Principles. IWR Report 92-R-1. Institute for Water Resources. Fort Belvoir, USA.

USEPA. 2008. National Water Program Strategy: Response to Climate Change. Washington, DC: USEPA.

Vörösmarty, C.J., P. Green, J. Salisbury, and R.B. Lammers. 2000. Global Water Resources; Vulnerability from Climate Change and Population Growth." *Science* 289: 284–288.

WCRP, 2006. Workshop "Understanding Sea Level-Rise and Variability", June 2006, UNESCO Paris: wcrp.ipsl.jussieu.fr/Workshops/SeaLevel Summary Statement : wcrp.ipsl.jussieu.fr/Workshops/SeaLevel/Reports/Summary_Statement_2006_1004.pdf.

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

Wolf, A. T., Stahl, K., & Macomber, M. F. 2003. Conflict and cooperation within international river basins: The importance of institutional capacity. Water Resources Update, 125. Universities Council on Water Resources.

World Bank. 2003. Water Resources Sector Strategy – Strategic Directions for World Bank Engagement. Report Number: 28114. Washington DC: The World Bank.

World Bank, 2004: *The Republic of Kenya. Towards a Water Secure Kenya. Water Resources Sector Memorandum*. Report No. 28398 – KE. Washington DC: The World Bank.

World Bank. 2006. *Ethiopia: Managing Water Resources to Maximize Sustainable Growth*. Country Water Resources Assistance Strategy.

World Bank. 2007. IDA and Climate Change: Making Climate Action Work for Development. Report Number: 41280. Washington DC: The World Bank.

World Bank. 2008a. Development and Climate Change: A Strategic Framework for the World Bank Group: Technical report. Report Number: 47893. Washington DC: The World Bank.

World Bank, 2008b. *Ethiopia: A country Study on Economic Impacts of Climate Change*. Report No. 46946-ET. Washington DC: The World Bank.

World Bank, 2009a. Assessment of climate Impact on Peru's hydrology. Development of a methodology. Progress Report No. 1.

World Bank. 2009b. Water and climate change: Impacts on groundwater resources and adaptation options. Water Anchor. Energy, Transport and Water Department. Washington DC: The World Bank.

WWF (World Wildlife Fund). 2009. *Flowing Forward: Informing Freshwater Biodiversity and Sustainable Management in a Shifting Climate* (draft report prepared for the World Bank).

ANNEX A: SUMMARY OF WATER PORTFOLIO BY REGION

Africa Region

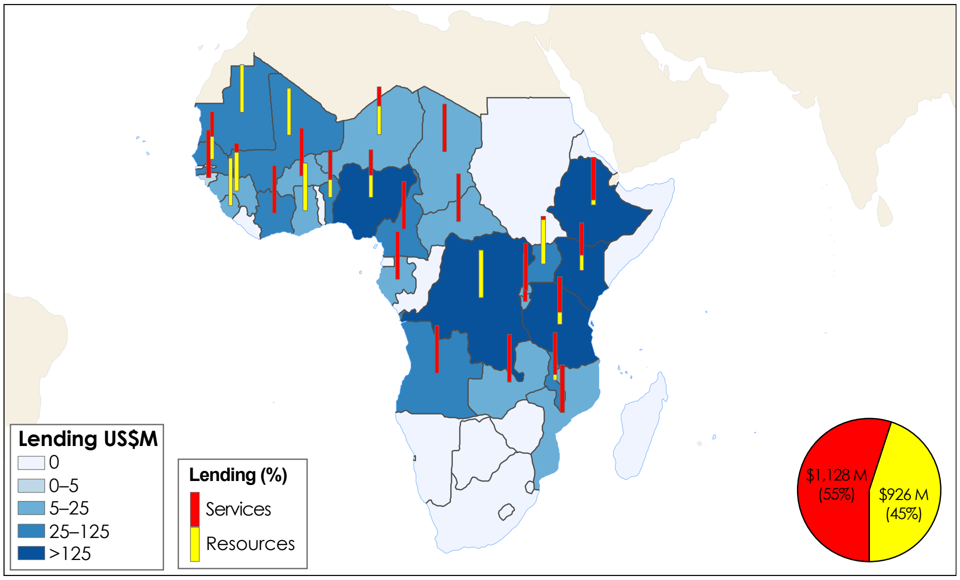
Overall water investment

Africa has committed a total of $2 billion in water investments in FY06–08, which account for 12% of the Bank's lending in the region (Figure A1). Among the regions, Africa has the highest level of water investments, both in terms of volume (23%) and number of projects (27%). The 2003 Water Resources Sector Strategy report projected growth in the water sector to this region, which has been confirmed by the increase in lending in the FY06–08 period with a yearly average of $685 million, the highest among all the regions for a total of 52 projects for the entire period.

Water investment by country

The water investments are distributed among 27 countries in the region including regional projects. Countries with the most number of projects are Ethiopia (seven), Kenya (six) and Tanzania (four) representing a third of all water projects in AFR. In terms of volume, the largest investments went to specific regional projects, and countries such as Ethiopia, Kenya and Nigeria. There are many small water resources investment projects in the region, however three of them are worth mentioning for their large investment amounts: *Regional and Domestic Power Markets Development Project-Inga Rehabilitation* ($271 million), *Niger Basin Water Resources Development and Sustainable Ecosystems Management* ($162 million) and the *Private Power Generation (Bujagali)* project ($115 million)—all in the category of multi-purpose systems.

Figure A1 Africa region water investment for the FY06–08 period



Source: World Bank, 2009.

Future water investments

AFR expects a major increase in number of water projects in the next two fiscal years[27], from an average of 17 projects per year (FY06–08) to an average of 27 projects per year (FY09–10)—the highest among the regions. In terms of lending volume, the pipeline is weaker than the current portfolio. Africa's pipeline represents 11% of the total water lending among the regions in FY09–10, a significant decrease compared to the active period with 23% of the total water investment. Moreover, water services systems are expected to dominate with 71% of the projected lending and 61% of the total number of projects.

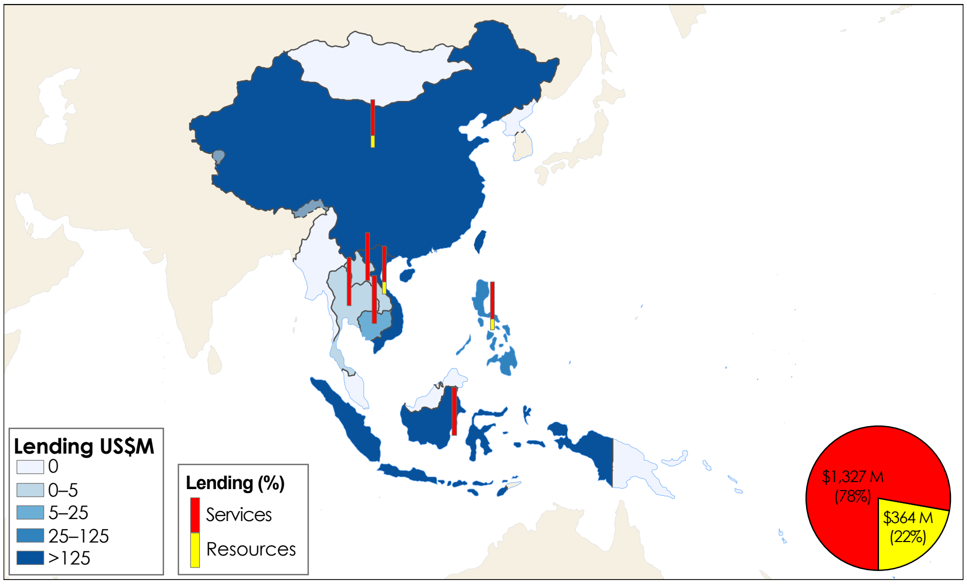
Looking at the pipeline distribution by system, the largest share of the projected lending is directed towards urban water and sanitation (53%) followed by irrigation and drainage (16%), water resources management (14%) and multi-purpose facilities (10%). A similar trend is seen in terms of number of projects, with urban water and sanitation systems dominating the water pipeline. In comparison to the active period, most increase is expected in water resources management for FY09–10.

East Asia and Pacific Region

Overall water investment

The total active water investments approved in FY06–08 is $1.7 billion representing 12% of the total Bank's lending in the region (Figure A2). Water investment in EAP accounts for 19% of the

Figure A2 East Asia and Pacific region water investment for the FY06–08 period



Source: World Bank, 2009.

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[27] Pipeline results should be read with caution because of the changes in approval dates, commitment amounts, etc, during the preparation phase of the project.

overall Bank's investment in water, which is the third highest share compared to other regions. In spite of the significant investment, water lending in the region has decreased significantly through the active period with a yearly average lending of $564 million for a total of 26 projects for the entire period.

Water investment by country

There are seven countries with water investments in the region for the FY06–08 period. Following the same pattern identified in the 2003 Water Resources Sector Strategy, China continues to dominate regional water lending with almost 70% of the overall water investments in the region (58% in terms of number of projects). Most of these investments are concentrated in urban water and sanitation (60%) consisting of projects of significant investment: *Henan Towns Water Supply and Sanitation project* ($143 million), *Second Liaoning Medium Cities Infrastructure project* ($142 million) and *Shanghai Urban Environment APL Phase 2* ($126 million). China also has a share of investment going into irrigation and drainage (14%) corresponding to a lending of $136 million (*Irrigated Agriculture Intensification Loan III*), and many small projects with water resources systems. Vietnam accounts for the second largest share of water investments (16%), followed by Indonesia (11%) and Philippines (4%). Except for China, there is little investment into water resources systems by other country in the region.

Future water investment

Water investments in FY09 and FY10 are expected to increase considerably compared to the FY06–08 period. The EAP region is expected to account for 24% of all the water investments (19% in terms of project number). Water services systems will continue to dominate, however at a lesser degree (67% in terms of investments and 57% in terms of number of projects).

Projections at the water system level show that 53% of the lending is in urban water and sanitation followed by 19% in multi-purpose systems. EAP is expected to have the largest share (36%) of watershed management investment among all regions. In terms of number of projects, urban water and sanitation system is also expected to dominate the pipeline. Most increase for the FY09–10 period is expected in water resources systems[28], more specifically in multipurpose facilities.

Europe and Central Asia Region

Overall water investment

The total active water investments approved in FY06–08 is $1.3 million, which represents 10% of the total Bank's lending in the region (Figure A3). Among the regions, Europe and Central Asia (ECA) region accounts for 14% of the total water investments and 15% of total number of projects. In the 2003 Sector Strategy portfolio review, ECA was identified as the region with the smallest share of water investments in the Bank. This is no longer the case as the region is increasing its lending, and has shown an average lending of $421 million with a total of 29 projects for the entire FY06–08 period.

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[28] Pipeline results should be read with caution because of the changes in approval dates, commitment amounts, etc, during the preparation phase of the project.

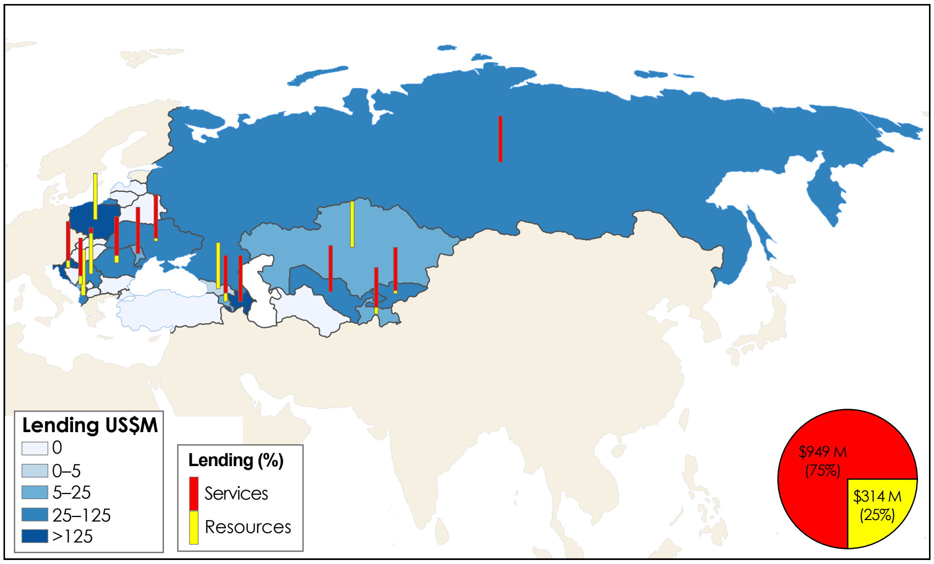
Water investment by country

Water investment is distributed between 16 countries in the region with the bulk of water investment concentrated in Azerbaijan (39%). Investment in the country is all going into urban water supply and sanitation with two significant projects, *National Water Supply & Sanitation* ($225 million) and *Second National Water Supply and Sanitation project* ($257 million). The second and third largest share of investments is in Poland (13%) with a project in flood control and water resources management, and Croatia (10%) with a project mainly in urban water and sanitation with components in flood control and water resources management. The remaining lending is distributed among 13 countries. In terms of number of projects, Azerbaijan has four projects followed by Armenia and Kyrgyz (with three projects each).

Future water investment

Water investments in the ECA region have increased substantially over the last couple of years and this trend is anticipated to continue over the FY09–10 period. The pipeline for ECA represents 12% of the total Bank's water investment. Water services systems is expected to continue to dominate, both in terms of investments (73%) and number of projects (67%), with an average lending of over $300 million per year. At the system level, significant increase in investment is expected for rural water and sanitation, irrigation and drainage and multi-purpose facilities. Urban water and sanitation will continue to be the main driver of water investments, however, irrigation and drainage and multi-purpose facilities are expected to account for a considerable share of total investments. Investments in flood control represent a smaller share (10%) in the pipeline; however, when compared to other regions, ECA still represents a substantial share (20%) of flood control investments in the Bank[29].

Figure A3 Europe and Central Asia region water investment for the FY06–08 period



Source: World Bank, 2009.

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[29] Pipeline results should be read with caution because of the changes in approval dates, commitment amounts, etc, during the preparation phase of the project.

Latin America and Caribbean Region

Overall water investment

The total active water investments approved in Latin America and Caribbean region (LCR) in the FY06–08 period is $1.2 billion which represents 8% of the total Bank's lending in LCR, the lowest compared to other regions (Figure A4). The LCR's portfolio corresponds to 13% of the overall Bank investments in water. Yearly average lending for LCR in FY06-FY08 is $390 million for a total of 40 projects for the entire period.

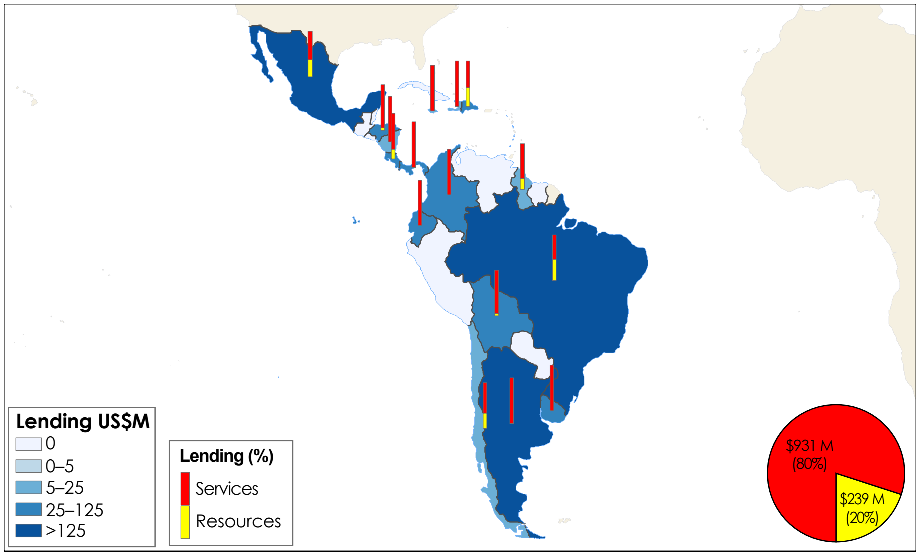
Water investment by country

For the FY06–08 period, there are 40 projects in 16 countries with most of the lending going to Argentina (23%), Mexico (23%) and Brazil (17%). The large amount of lending in Argentina and Mexico represent only three projects in each country: Argentina focuses on urban water and sanitation with a small portion towards watershed management, while Mexico has a balanced investment between urban water and sanitation and water resources management. There is one project in each country worth mentioning due to their large investment: *Infrastructure Project for the Province of Buenos Aires APL2* ($146 million) in Argentina and *Climate Change DPL* ($250 million) in Mexico. Although there is significant water investment in Brazil (a total of $200 million), the lending is well distributed between ten projects with most investment going into water resources management and urban water and sanitation.

Future water investment

Total water investment for the FY09–10 is expected to double in comparison to the FY06–08 period accounting for 24% of the overall Bank's pipeline for water. This increase is the highest of

Figure A4 Latin America and Caribbean region water investment for the FY06–08 period



Source: World Bank, 2009.

any region with most lending directed towards water services (74%), although lending for water resources is also expected to increase by almost threefold.

Projection at the water system level is not expected to vary significantly from the current portfolio. About 64% of lending and 42% of projects is expected to be in urban water and sanitation followed by 25% of lending and 29% of projects into water resources management. Significant increase in investment is expected not only for water resources management, but also for rural water and sanitation. Increase in lending is also expected in urban water and sanitation and irrigation and drainage, though to a lesser degree[30].

Middle East and North Africa Region

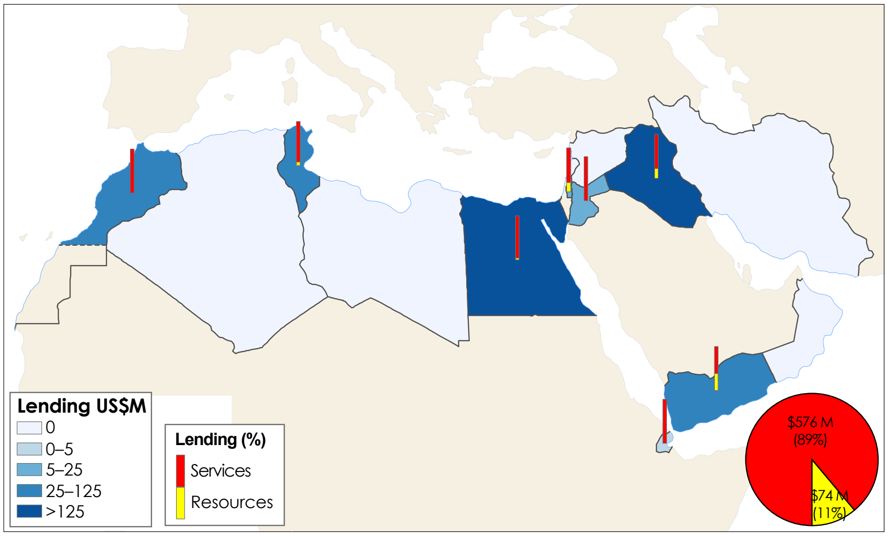
Overall water investment

The Middle East and North Africa (MNA) region has committed a total of $650 million in water investments for FY06–08, which accounts for 14% of the overall regional investments (Figure A5). Although a significant portion of investment is going to water, compared to other regions, this represents a small portion (7%) of the Bank's total commitment in water. Despite the relative low water investment, lending increased during the last three fiscal years with a yearly average investment of $217 million corresponding to a total of 16 projects for the entire period.

Water investment by country

Water investments are distributed among eight countries in the region. Of the 16 projects approved in the FY06-FY08 period (with ten projects corresponding to 2008 alone), Egypt has the largest

Figure A5 Middle East and North Africa region water investment for the FY06–08 period



Source: World Bank, 2009.

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[30] Pipeline results should be read with caution because of the changes in approval dates, commitment amounts, etc, during the preparation phase of the project.

share of commitments (40%), followed by Iraq (26%), Tunisia (16%), Morocco (9%), and Yemen (6%). There are three significant projects in the region, two in Egypt (*West Delta Water Conservation and Irrigation Rehabilitation project* of $141 million and the *Integrated Sanitation & Sewerage Infrastructure project* of $120 million) and one in Iraq (*Emergency Water Supply Project* of $104 million) corresponding to 56% of the total water regional investment. Of the six projects with water resources systems, the one with the largest commitment is in Iraq—*Dokan and Derbandikhan Emergency Hydro Power Project* ($40 million).

Future water investment

For the FY09–10 period[31], the region is expected to increase its yearly average lending investment in the sector. Among the regions, MNA would represent 5% of the overall water commitments in the Bank, slightly lower than the FY06–08 period. Most of the lending is again expected for projects with water services (86%) and will continue being the highest share of any region.

Projection at the water system level show most of the lending going to urban water and sanitation, irrigation and drainage, and water resources management, each representing a significant portion of the total water pipeline in the region (44%, 37% and 14% respectively). There is a percentage increase in lending expected for water resources management and irrigation, while there is a percentage decrease expected for rural water and sanitation, showing a significant decline from the FY06–08 period.

South Asia Region

Overall water investment

South Asia region (SAR) has committed a total of $1,945 million in water investment for FY06–08, accounting for 14% of the overall regional investment (Figure A6). Among the regions, SAR represents 22% of the overall water investment (15% in terms of number of projects), which is the second largest share after AFR. Water investment in the region has steadily increased during this period, with yearly average of $648 million corresponding to a total of 28 projects for the entire period.

Water investment by country

Water investment in SAR for FY06–08 is distributed among six countries in the region. India is the driver in the region representing 68% of water investments (less so in terms of number of projects –36%). Pakistan has a considerable share of investments (10%), followed by Bangladesh, Nepal, Afghanistan (6% each), and Sri Lanka (4%). The projects with the largest investments for this period are in India: *Rampur Hydropower Project* ($400 million) and *Tamil Nadu Irrigated Agriculture Modernization and Water-Bodies Restoration and Management Project* ($291million). Pakistan has also a large irrigation project: *Sindh Water Sector Improvement Project Phase I* ($120 million).

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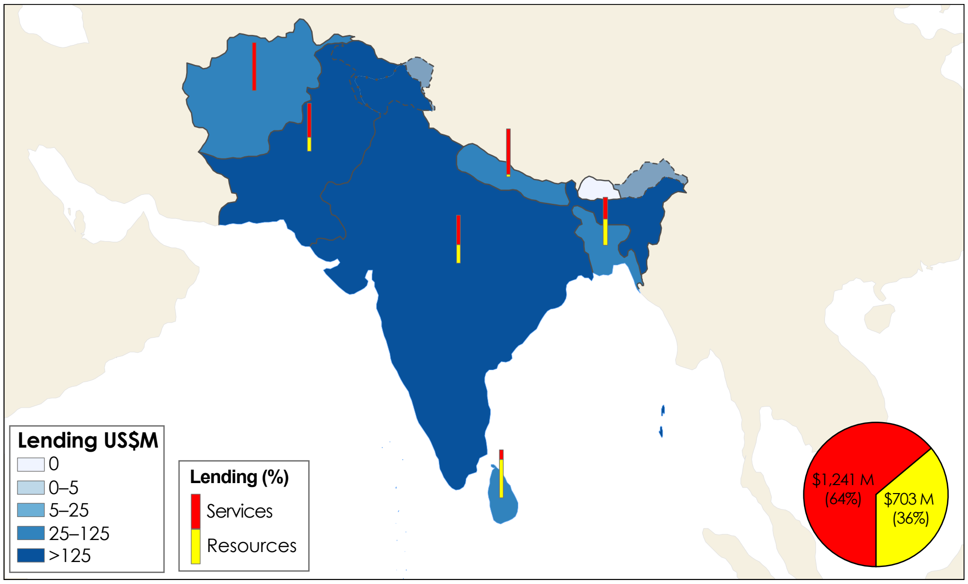
[31] Pipeline results should be read with caution because of the changes in approval dates, commitment amounts, etc, during the preparation phase of the project.

Figure A6 South Asia region water investment for the FY06–08 period



Source: World Bank, 2009.

Future water investment

In the coming two fiscal years (FY09-FY10), the projection for water lending in the SAR region is expected to increase to an average lending of over $1 billion compared to $648 million per year for the FY06–08 period. SAR is expected to represent 26% of the Bank's lending in water. Projects with water services systems are anticipated to dominate 62% of the investments, with a stronger focus on urban water and sanitation (37%) and irrigation and drainage (26%). Likewise, lending for multi-purpose facilities (25%) is expected to continue strong and to be the highest of any region. There is also a large lending increase expected for flood control and watershed management systems. Unlike the FY06–08 period, SAR is expected to decrease its investment in rural water and sanitation systems, thus the region is no longer expected to be the largest contributor of investments towards that system.[32]

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[32] Pipeline results should be read with caution because of the changes in approval dates, commitment amounts, etc, during the preparation phase of the project.

ANNEX B: RISK-BASED DECISION MAKING FRAMEWORKS

United Kingdom Climate Impacts Programme

In May 2003, UKCIP published a technical report titled *Climate Adaptation: Risk, Uncertainty and Decision-making* (Willows and Connell, 2003). This report "recommends a structured framework and associated guidance to promote good decision-making" (Willows and Connell, 2003, p. v). The framework consists of the eight stages listed here and illustrated in Figure B1.

- Stage 1: Identify problem and objectives
- Stage 2: Establish decision-making criteria
- Stage 3: Assess risk
- Stage 4: Identify options
- Stage 5: Appraise options
- Stage 6: Make decision
- Stage 7: Implement decision
- Stage 8: Monitor, evaluate, and review.

According to UKCIP: "The aim of using the framework is for the decision-maker to identify where climate change is a material consideration. Where climate or climate change are significant, the decision-maker should aim to identify adaptation options for the decision (such as no regret options) that are robust to the key sources of uncertainty" (Willows and Connell, 2003, p. 6).

Pros

This framework focuses on the entire decision-making context. Issues of problem definition are addressed in stage 1 and rechecked in stage 6. "Formulating the issue represents a critical stage for the decision-maker. Before embarking on a decision-making process, it is essential to understand the reasons for the decision being made, the decision-maker's broad objectives, and the wider context for the decision" (Willows and Connell, 2003, p. 10).

This framework quickly addresses substantive issues by operationalizing the stage 1 problem definition in stage 2. "This stage sets out the establishment of criteria for decision-making. The broad objectives of the decision-maker, set out under stage 1, need to be translated into operational criteria that can be used in a formal risk assessment, and against which the performance of different options and the subsequent decision can be appraised" (Willows and Connell, 2003, p. 14). Although not every adaptation policy is amenable to such formal analysis, using formal criteria, when possible, maximizes accountability, enables unambiguous evaluation of policy success or failure, and assists in identifying informational needs.

UKCIP attempted to make its framework context sensitive at key points such as the stage 3 risk assessment and the stage 5 option appraisal by indicating that under certain circumstances, resource- and time-intensive steps can be skipped entirely. The conditional nature of these steps, however, faces severe practical limitations, as discussed below under "cons."

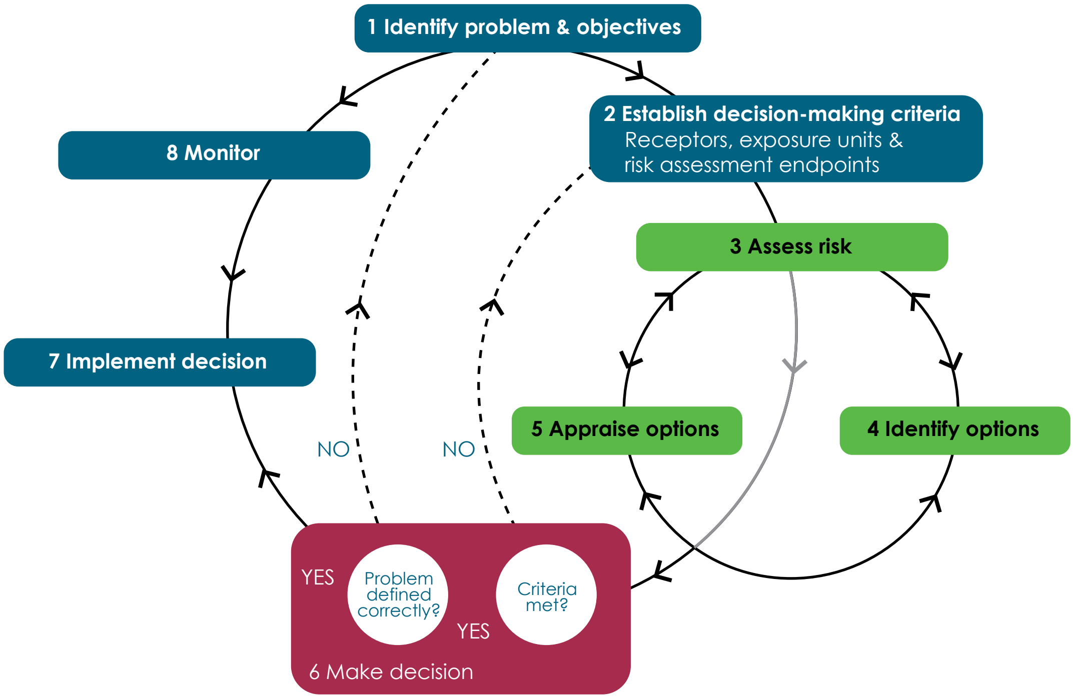
UKCIP included stage 7 implementation and stage 8 monitoring as part of their framework. However, these elements of the decision-making process are not discussed because: "The prime purpose of these guidelines is to help the decision-maker reach a decision and we do not therefore discuss in detail the "best" means to implement and monitor a decision" (Willows and Connell, 2003, p. 39).

Cons

The stage 3 risk assessment in this framework is a detailed analysis that, in our judgment, requires expert practitioners to implement. Despite the attempt to simplify this step by subdividing it into three "tiers": "risk screening," "generic quantitative risk assessment," and "detailed quantitative risk assessment," its complexity may be a barrier to its use by decision-makers. Namely, by subdividing and contextualizing this step in the framework, decision-makers may either ignore this step or delegate it to technical experts. It is not clear that technical experts are either needed for many decisions or the appropriate authority for deciding when sufficient knowledge has been accumulated given time and resource constraints. The stage 5 option appraisal also has three tiers and may suffer from similar problems.

Stage 4, "identify options," follows the stage 3 risk assessment. In reality, many adaptations exist that are no regret policies which offer benefits under current climate as well as under projected changes in climate. Such policies do not require the preceding stage 3 risk assessment for their justification. In many circumstances, engaging in stage 4 before stage 3 can reduce the time and resource demands of decision-making by identifying policy options that do not require a risk assessment. Indeed, it is our contention that options should be identified early in the decision-making process.

Figure B1 The UKCIP framework



Source: Willows and Connell, 2003, p. 7, Fig. 1.

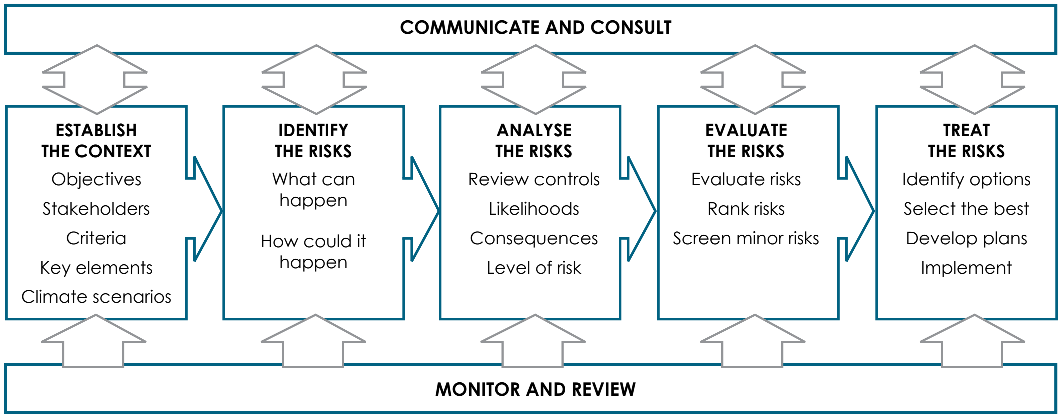
Although this framework claims to be "circular" and "iterative" by incorporating "feedback" mechanisms and promoting "adaptive management," many people, including decision-makers, may have difficulty understanding how different stages of a process like this feedback on one another. According to Figure B1, almost every stage in this framework should feed back to earlier stages. Only stage 6, "make decision," has formal logical criteria for deciding whether to revisit previous stages. In essence, the interrelationships between framework stages may be too complex to be useful to many decision-makers who are limited by incomplete information and multiple demands on their time.

Australian Greenhouse Office

In 2006, the Australian Greenhouse Office published a report titled *Climate Change Impacts & Risk Management: A Guide for Business and Government* (Broadleaf and MJA, 2006). According to the report, "The Guide provides a framework for managing the increased risk to organizations due to climate change impacts. The prime focus of the Guide is on the initial assessment and prioritization of these risks" (Broadleaf and MJA, 2006, p. 9). Notably, this framework uses the Australian and New Zealand Standard for Risk Management, AS/NZS 4360 (Standards Australia, 2004), to extend the application of this widely used guidance on risk management in the public and private sectors to risks generated by climate change and its impacts. The framework consists of the five steps and two umbrella activities listed here and illustrated in Figure B2.

- Step 1 Establish the context
- Step 2 Identify the risks
- Step 3 Analyze the risks
- Step 4 Evaluate the risks
- Step 5 Treat the risks
- Umbrella activities
  - Communication and consultation
  - Monitor and review

Figure B2 The Australian framework



Source: Broadleaf and MJA, 2006, p. 19, Fig. 5.

Pros

The Australian framework offers a simple, linear decision process that can be implemented by a wide range of people without requiring specific expertise in risk assessment methodologies. This is particularly important in creating a framework that can be used by decision-makers. According to the Australian Greenhouse Office, "The process requires only standard climate scenarios, a general understanding of the impacts of climate change, comprehensive understanding of the business or organization and sound professional judgment" (Broadleaf and MJA, 2006, p. 18).

Even though the decision process as outlined is linear, it also allows for interconnectedness through the two umbrella functions of communication/consultation and monitor/review. According to the Greenhouse Office, "Communication and consultation are key components of any risk management process and are required at each step. Success relies on achieving a high level of creative input and involving all parties with a role to play in identifying, assessing and managing climate change risks. In both the planning and execution of the risk management process it is important to ensure that all those who need to be involved are kept informed of developments in the understanding of risks and the measures taken to deal with them" (Broadleaf and MJA, 2006, p. 20). Also, regarding the monitor/review umbrella function, "The outputs of all steps of the risk management process must be kept under review so that, as circumstances change and new information comes to hand, plans can be maintained and kept up to date" (Broadleaf and MJA, 2006, p. 20).

The Australian framework also allows for multiple levels of analysis as circumstances dictate. "To allow effort to be directed towards the highest priority issues, a two-stage approach to risk assessment is recommended to users of this Guide: (1) An initial assessment identifies and sifts risks quickly, followed by treatment, planning, and implementation for those risks that clearly require it; and (2) Detailed analysis is used where additional information is needed to determine whether treatment is required or what form of treatment to adopt" (Broadleaf and MJA, 2006, p. 21). This allows for the differential treatment of policy actions that are no regret and those that may have significant costs or externalities that merit greater analysis and consideration.

Cons

The front end of this framework includes many critical tasks within step 1, "establish the context," such as "clarifying explicitly the objectives of the organization," "establishing success criteria against which risks to the organization's objectives can be evaluated," and "identifying stakeholders and their objectives and concerns" (Broadleaf and MJA, 2006, p. 19). However, because so many important tasks are aggregated into a single step in the framework, some of those tasks could be neglected or presumed, and decision-makers might proceed to the technical aspects of risk assessment without critically considering these front-end tasks.

The Australian framework does not contain any information or guidance about turning a decision into action. Essentially, this framework neglects the important tasks of policy construction, promotion, and implementation—failing not only to discuss them, but even to mention them as part of the decision process.

This framework proposes to execute a decision process and risk assessment through a single methodology—the workshop format. This includes steps 2, 3, and 4, the identification, analysis, and evaluation of risks. Although qualitatively assessing risks can be very useful for involving stakeholders and for avoiding the tendency to get bogged down in technical analyses that may not be necessary to take action, there are times when a more formal risk assessment is appropriate. This is particularly the case when the decision-maker is a technical expert, when costs may be very high, when the range of risks due to climate change is very wide, when significant uncertainties prevent an accurate assessment of risk likelihood or consequence, and so on. Although the detailed risk assessment is meant to address these issues, the Australian Greenhouse Office still claims, "The process of implementing the detailed analysis will, in most cases, be particular to your organization and to the different risks faced by your organization. For this reason, it is not feasible or appropriate to offer specific guidance on the detailed analysis" (Broadleaf and MJA, 2006, p. 54).

ANNEX C: ADAPTATION OPTIONS FOR MULTI-PURPOSE INFRASTRUCTURE

Dam structure

Concrete dams have greater adaptive capacity than embankment dams, owing to the fact that they are normally founded on rock, and can be strengthened to withstand higher flood loadings—including overtopping in some circumstances. Embankment dams cannot be modified readily to the same extent, and are therefore more challenging to adapt.

Since foundation conditions often dictate the type of dam that can be economical for a given project site, criteria that involve climate change impacts will likely not drive the decision. Nonetheless, climate factors should be considered in evaluating the type and size of dam to be constructed. Siting studies may consider configuring the dam in such a way as to enable economical future raising, perhaps through the use of saddle dams along reservoir rims. Another strategy would be to consider use of multiple sites to achieve the head or storage objectives of a single-dam development. In such cases, it may be that two smaller developments can have a smaller environmental footprint than one large dam, thereby providing added value to this solution.

Reservoir storage

Reservoir storage and yield is a function of the storage volume required to produce the desired yield against a certain probability of exceedance (or failure). It is one of the early planning activities because much of the built infrastructure and the configuration of dam components depend upon this parameter.

Once a given site for the reservoir is selected (based on a host of geologic, hydrologic, and topographic criteria) then the ability to provide the desired yield is a function of the minimum and maximum reservoir levels necessary to provide the active storage. The minimum level is determined based upon sedimentation criteria, while the top of dam elevation is set by the optimization of flood routing studies and dam stability in order to establish the optimum trade-off between flood storage and peak reduction versus spillway head and discharge capacity.

So this component governs the dam height and spillway capacity, which are often the two most expensive components of the project. This also has socioeconomic implications relating to resettlement of marginal populations.

Use of the term “optimum” immediately raises a flag, because it implies that a host of competing criteria has been used to determine a trade-off that is invariant. This is counter to the entire concept of potential unknown climate change impacts that must be designed against. For future projects in the planning and design stage, it is now prudent to consider more variability and another degree of freedom than has traditionally been the case.

Use of top down probabilistic analysis may require information and data that is not available (or highly uncertain). An interesting alternative hereto is the use of risk—based decision models, which generate a large number of scenarios based on Monte-Carlo simulations and then analyze the outcomes for a range of scenarios.

For existing project vulnerabilities, adaptation will involve means of enlarging the reservoir storage volume, either by raising the maximum operating level, or lowering the minimum level, or both.

Lowering the minimum level is problematic, since it is a function of sedimentation and would require expensive underwater construction. Raising the maximum level could require modifications to upgrade dam stability or increase spillway capacity, or both. These modifications can also be very expensive. Another option for projects which are part of a multi-project basin development is to distribute the storage among multiple locations, either at existing reservoirs or at new sites, where additional storage can economically be provided.

Service & auxiliary spillways

Depending upon the project configuration, the service and auxiliary spillway system can be the second-most expensive component of the project, after the dam. An exception would be a low-head run-of-river project where the dam itself serves as an overflow spillway.

For large storage reservoirs, a reservoir routing analysis is done to analyze and optimize the trade-off between flood inflow, reservoir storage, and project outflow so that the spillway system is properly designed. Service spillways are generally massive concrete structures, founded on sound rock or constructed integrally with a concrete dam. Auxiliary spillways normally traverse one of the dam abutments, and can consist of an overflow weir and channel, or may have an erodible “fuse-plug” control to prevent premature operation of the auxiliary spillway.

The primary criterion for designing spillways for climate change is the selection of the flood peak discharge and volume that will govern the design. In most cases, this is the Probable Maximum Flood (PMF), which is derived from the Probable Maximum Precipitation (PMP), along with watershed characteristics. Since, in the climate changed future, both the precipitation and the watershed characteristics (due to temperature, vegetation, and soil moisture and groundwater conditions) can vary, solutions must consider variations in both rainfall and runoff characteristics.

Even in the absence of a “return period” concept in the case of the PMF, the uncertainty of how PMP and watershed characteristics may change in future presents a challenge to the designer. In the developed world, hydrometeorology advances have been incorporated into PMP and PMF studies to enable site-specific assessments that provide a more rational basis for project planning and design. The cost of such investigations is often economical when compared to the cost of providing additional spillway capacity.

Retrofitting existing spillways to provide additional capacity has been a routine activity in the developed world, where advances in hydrologic analysis, dam failures, and large populations at risk have led to regulatory requirements to provide increased flood protection at “high-hazard” dams. These measures can include:

- Providing gates atop existing ungated spillways;
- Raising gate heights, or adding additional gated bays;
- Stability improvements to allow overtopping of critical structures without failure;
- Provision of additional auxiliary spillway capacity; or
- Combinations of the above.

A common thread among all of these options is high cost, underscoring the benefits of designing and building “adequate” spillway systems from the beginning.

For less severe, more frequent flood conditions, operational measures to predict flood events either seasonally or in real-time may be employed. This may enable pre-lowering ("voiding") of the reservoir storage in order to better manage expected flood runoff or events. For example, the City of New York uses snow survey data to enable "voiding" of downstream water supply reservoirs in order to provide flood control benefits without adversely impacting water supply. The volume of voiding is limited to one-half of the predicted snowpack, thereby ensuring that the reservoir will refill for the coming supply season.

Intake and low-level outlet works

Intakes. Much of the above discussion on options for increasing reservoir storage is applicable to the intake works, as this is the means of exploiting the available storage. Raising the intake works along with a raised reservoir is likely required, since criteria for maximum allowable entrance velocities (to prevent debris and fish entrainment) govern the size, location and number of intake ports required.

Modification of existing intakes to accommodate lower operating levels is difficult and expensive to achieve. Building such flexibility into the planning and design of new intakes is the recommended approach. Of equal importance is to provide proper watershed management to minimize soil erosion and siltation problems in the reservoir. In tropical and subtropical areas, vegetation management—both terrestrial and aquatic—is also necessary. Hydropower production in Zambia has been recently impacted due to excessive aquatic vegetation clogging hydropower plant intakes.

Low-Level Outlets. Adapting low-level outlet works to climate change impacts presents many of the same challenges as tunnels. Often designed to a fixed capacity and size, and imbedded within project structures below normal operating levels, such outlets are not easily or economically adapted. Possible strategies may include:

- Design outlet works with redundant water passages that can be closed off or opened as future conditions warrant; or
- Provide parallel component systems—water supply outlets and spillway outlets, for example—that can be used interchangeably or in tandem as needs arise.

Hydropower plant

Key design elements of hydropower plants are the intakes, water conductors, and turbine-generator sets. Once these elements are sized and built, they are not readily changed. In the past, it has been common practice in the planning and design stages to consider provisions for staged development of the power component, providing block-outs and skeleton bays for future construction of additional water conductors and installation of turbine-generator sets. However, this adds to the upfront cost while risking a stranded investment, if the need for the expansion does not arise.

Hydroelectric equipment is designed to operate within a given range of head, discharge and efficiency conditions. There is some flexibility within a given equipment design for (less) efficient operation above and below the design optimum. However, the number of units, sizes of intakes and water conductors, and related structural components are relatively fixed once they are sized and constructed.

Another key factor in adapting hydroplants to climate change is the dispatch criteria for fitting the hydropower plant into the overall system demand profile. Hydroplants are frequently operated as “load-following” or “peaking” plants, because of their inherent ability to increase or decrease generating capacity and energy output on a short-term time horizon.

Adapting hydropower plants to a climate-change future requires comprehensive analysis of power and energy demand to be served, water availability under a relevant range of future climate scenarios, and cost of power versus cost of construction to achieve the required return on investment (ROI) from the plant. Consideration of these factors will inevitably lead to providing multiple units of equal or varying capacity, so that a wide range of production and demand scenarios can be accommodated.

Tunnels

Tunnels often serve project performance needs, taking maximum advantage of the available driving head from the reservoir. Sizing of these structures is usually done to a fairly tight specification of design discharge, and they have specific requirements (e.g., requiring plant shutdown to effect any modifications) that can make post-construction modifications difficult and expensive.

In certain applications, use of tunnels as water conductors for hydropower plants, outlet works, and even spillway systems is a sound technical and economic decision. However, for many of the same reasons described above for hydroplants, they are not readily modified or retrofitted post-construction.

This again speaks to the premium placed upon the upfront planning and design activities necessary to size the works and, where possible, climate-proof them. One option for tunnels is to design them to operate as open channels, but with the ability to function safely and reliably as pressure conduits at higher discharge levels.

Open channels

Open-channel conveyances or canals provide some measure of adaptability in response to climate change impacts. Solutions will generally involve reducing freeboard, or widening or deepening the cross-section by excavation. It is more expensive to modify a lined channel than an unlined channel, and even deepening of an unlined channel might require the introduction of a lining if significantly different foundation materials are encountered. Depending upon freeboard and lining conditions, canals can operate at higher-than-design discharges by modifying the control structures to allow it. It may therefore be that the adaptability of the control structures governs the adaptability of the canal, rather than the channel itself.

ANNEX D: GLOSSARY OF TERMS

(Source: Bates et al, 2008, except where noted)

Adaptation

Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. Various types of adaptation exist, e.g. anticipatory and reactive, private and public, and autonomous and planned. Examples are raising river or coastal dikes, the substitution of more temperature-shock resistant plants for sensitive ones, etc.

Adaptive capacity

The whole of capabilities, resources and institutions of a country or region to implement effective adaptation measures.

Climate

Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate change

Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the United Nations Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes.

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, and accounting 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 parameterisations are involved. Coupled Atmosphere-Ocean General Circulation Models (AOGCMs) provide a representation of the climate system that is near the most comprehensive end of the spectrum currently available.

There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal and interannual climate predictions.

Climate projection

A projection of the response of the climate system to emissions 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 are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised and are therefore subject to substantial uncertainty.

Climate scenario

A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate. A climate change scenario is the difference between a climate scenario and the current climate.

Climate system

The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and anthropogenic forcings such as the changing composition of the atmosphere and land-use change.

Climate variability

Climate variability refers to 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 within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

Confidence

As defined by the IPCC, the degree of confidence in being correct is described as follows:

Very high confidence	At least 9 out of 10 chance of being correct
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than a 1 out of 10 chance

Detection and attribution

Climate varies continually on all time scales. ***Detection*** of climate change is the process of demonstrating that climate has changed in some defined statistical sense, without providing a reason for that change. ***Attribution*** of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence.

Downscaling

Downscaling is a method that derives local-to regional-scale (10 to 100km) information from larger-scale models or data analyses. Two main methods are distinguished: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution or high-resolution global models. The empirical/statistical methods develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the downscaled product depends on the quality of the driving model.

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. Concentration scenarios, derived from emission scenarios, are used as input to a climate model to compute climate projections. In IPCC (1992) a set of emission scenarios was presented which were used as a basis for the climate projections in IPCC (1996). These emission scenarios are referred to as the IS92 scenarios. In the IPCC Special Report on Emission Scenarios (Nakićenović and Swart, 2000) new emission scenarios, the so-called SRES scenarios, were published.

Ensemble

A group of parallel and model simulations used for climate projections. Variation of the results across the ensemble members gives an estimate of uncertainty. Ensembles made with the same model but different initial conditions only characterise the uncertainty associated with internal climate variability, whereas multi-model ensembles including simulations by several models also include the impact of model differences. Perturbed-parameter ensembles, in which model parameters are varied in a systematic manner, aim to produce a more objective estimate of modelling uncertainty that is possible with traditional multi-model ensembles.

Exposure

In this context of this report, exposure refers to Bank projects and/or regional investments being subjected to negative changes in annual runoff (from present day values) in the year 2030 or 2050. The Climate Change Exposure Index was defined as follows for all projects except flood control projects:

Exposure Index	*Description*
Water systems (non flood control)	
Low	% reduction in annual runoff…. Less than 5%
Medium	% reduction in annual runoff…. Between 5 and 15%
High	% reduction in annual runoff…. More than 15%
Flood control system	
Low	% reduction in annual runoff…. More than 15%
Middle	% reduction in annual runoff…. Between 5 and 15%
High	% reduction in annual runoff…. Less than 5%

Flexibility

The flexibility of a system refers to its ability to adapt to a wide range of operating conditions through relatively modest and inexpensive levels of redesign, refitting or reoperation (Hashimoto, T. et al., 1982a).

General Circulation Model

See *Climate model*.

Greenhouse effect

Greenhouse gases effectively absorb thermal infrared radiation, emitted by the Earth's surface, by the atmosphere itself due to the same gases, and by clouds. Atmospheric radiation is emitted to all sides, including downward to the Earth's surface. Thus greenhouse gases trap heat within the surface troposphere system. This is called the greenhouse effect. Thermal infrared radiation in the troposphere is strongly coupled to the temperature of the atmosphere at the altitude at which it is emitted. In the troposphere, the temperature generally decreases with height. Effectively, infrared radiation emitted to space originates from an altitude with a temperature of, on average, –19°C, in balance with the net incoming solar radiation, whereas the Earth's surface is kept at a much higher temperature of, on average, +14°C. An increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere, and therefore to an effective radiation into space from a higher altitude at a lower temperature. This causes a radiative forcing that leads to an enhancement of the greenhouse effect, the so-called enhanced greenhouse effect.

Greenhouse gas (GHG)

Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine and bromine containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

Hydrological cycle

The cycle in which water evaporates from the oceans and the land surface, is carried over the Earth in atmospheric circulation as water vapour, condensates to form clouds, precipitates again as rain or snow, is intercepted by trees and vegetation, provides runoff on the land surface, infiltrates into soils, recharges groundwater, discharges into streams, and ultimately, flows out into the oceans, from which it will eventually evaporate again (AMS, 2000). The various systems involved in the hydrological cycle are usually referred to as hydrological systems.

(Climate change) impacts

The effects of climate change on natural and human systems. Depending on the consideration of adaptation, one can distinguish between potential impacts and residual impacts:

- *Potential impacts*: all impacts that may occur given a projected change in climate, without considering adaptation.
- *Residual impacts*: the impacts of climate change that would occur after adaptation.

Likelihood

As defined by the IPCC, the likelihood of the occurrence/outcome is described below:

Virtually certain	>99% probability of occurrence
Very likely	90 to 99% probability
Likely	66 to 90% probability
About as likely as not	33 to 66% probability
Unlikely	10 to 33% probability
Very unlikely	1 to 10% probability
Exceptionally unlikely	<1% probability

Mitigation

Technological change and substitution that reduce resource inputs and emissions per unit of output. Although several social, economic and technological policies would produce an emission reduction, with respect to Climate Change, mitigation means implementing policies to reduce greenhouse gas emissions and enhance sinks.

No-regrets policy

A policy that would generate net social and/or economic benefits irrespective of whether or not anthropogenic climate change occurs.

Projection

A potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Projections are distinguished from predictions in order to emphasize that projections involve assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised, and are therefore subject to substantial uncertainty.

Reliability

Reliability is defined as the likelihood that services are delivered (no failure) within a given period, expressed as a probability. High probabilities indicate high reliability (Hashimoto, T. et al., 1982b).

Resilience

A. 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.
B. Resiliency is the speed at which the system recovers from a failure, on average. Shorter recovery periods indicate higher resiliency (Hashimoto, T. et al., 1982b).

Risk

The potential for realization of unwanted, adverse consequences; usually based on the expected result of the conditional probability of the occurrence of the event multiplied by the consequence of the event, given that it has occurred. What makes a situation risky rather than uncertain is the availability of objective estimates of the probability distribution. (USACE, 1992)

Robustness

In a water resources system, robustness refers to the extent to which a system design is able to deliver optimal or near-optimal levels of service over a range of demand (input) and supply (resource) conditions (Hashimoto, T. et al., 1982a).

Scenario

A plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections, but are often based on additional information from other sources, sometimes combined with a narrative storyline.

Sensitivity

Sensitivity is the degree to which a system is affected, either adversely or beneficially, by

climate variability or climate change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).

Stationarity

Stationarity assumes that natural systems fluctuate within an unchanging envelope of variability. Stationarity is a foundational concept that permeates training and practice in water-resource engineering. It implies that any variable (e.g., annual streamflow or annual flood peak) has a time-invariant (or 1-year–periodic) probability density function (pdf), whose properties can be estimated from the instrument record. Under stationarity, pdf estimation errors are acknowledged, but have been assumed to be reducible by additional observations, more efficient estimators, or regional or paleohydrologic data. The pdfs, in turn, are used to evaluate and manage risks to water supplies, waterworks, and floodplains (Milly et al., 2008).

Threshold

The level of magnitude of a system process at which sudden or rapid change occurs. A point or level at which new properties emerge in an ecological, economic or other system, invalidating predictions based on mathematical relationships that apply at lower levels.

Uncertainty

A. An expression of the degree to which a value (e.g., the future state of the *climate system*) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain *projections* of human behaviour. Uncertainty can therefore be represented by quantitative measures, for example, a range of values calculated by various models, or by qualitative statements, for example, reflecting the judgment of a team of experts.

B. Uncertain situations are those in which the probability of potential outcomes and their results cannot be described by objectively known probability distributions, or the outcomes themselves, or the results of those outcomes are indeterminate (USACE, 1992)

United Nations Framework Convention on Climate Change (UNFCCC)

The Convention was adopted on 9 May 1992 in New York and signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Community. Its ultimate objective is the "stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". It contains commitments for all Parties. Under the Convention, Parties included in Annex I (all OECD member countries in the year 1990 and countries with economies in transition) aim to return greenhouse gas emissions not controlled by the Montreal Protocol to 1990 levels by the year 2000. The Convention entered in force in March 1994.

Vulnerability

A. Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

B. Vulnerability refers to the severity of the likely or expected consequences of failure (Hashimoto, T. et al., 1982b).

References

AMS, 2000: AMS Glossary of Meteorology, 2nd Edition. American Meteorological Society, Boston, MA. http://amsglossary.allenpress.com/glossary/browse.

Hashimoto, T., D.P. Loucks, and J.R. Stedinger. 1982a. Robustness of water resources systems. *Water Resources Research* 18(1):21–26.

Hashimoto, T., J.R. Stedinger, and D.P. Loucks. 1982b. Reliability, resiliency and vulnerability criteria for water resource system performance evaluation. *Water Resources Research* 18(1):14–20.

IPCC, 1992. Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment [Houghton, J.T., B.A. Callander, and S.K. Varney (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

IPCC. 1996. Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. J. T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell. (eds.). Cambridge, England: Cambridge University Press.

IPCC, 2008, Technical Paper on Climate Change and Water, IPCC Secretariat, Geneva, Switzerland.

Milly et al. 2008. Stationarity is Dead: Wither Water Management? *Science* vol.319.

Nakićenović, N. and R. Swart (Eds.), 2000: *Special Report on Emissions Scenarios*. Cambridge University Press, 599 pp.

USACE (US Army Corps of Engineers). 1992. Guidelines for Risk and Uncertainty Analysis in Water Resources Planning, Vol 1 – Principles. IWR Report 92-R-1. Institute for Water Resources. Fort Belvoir, USA.