CGE Training Materials for Vulnerability and Adaptation Assessment

Chapter 6
Water Resources

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6.1. Introduction

Climate change is likely to alter the hydrologic cycle in ways that may cause substantial impacts on water resource availability, timing and changes in water quality. The temporal and spatial distribution of precipitation, its intensity and frequency of occurrence and whether it falls as rain or snow in cold regions are likely to change to different extents depending on regional climatic and hydrological factors.

In addition, changes in run-off could arise from the fact that the amount of water evaporated from the landscape and transpired by plants will change with changes in soil moisture availability and plant responses to elevated carbon dioxide (CO_2) concentrations. This will affect stream flows and groundwater recharge.

Also, climate change driven alterations to the hydrologic cycle will come along with significant changes that have, continue to or will occur within river basins. Land-use changes such as conversion from forest to cropland, from cropland to urban area, from grassland to cropland and land-use intensification will alter the hydrologic cycle. These changes will affect both water availability and demand. Changes in the patterns and levels of water demand in the future will provide additional challenges to effective adaptive responses to climate change and water resource management.

This chapter provides an approach to consider water resources in the development of the vulnerability and adaptation (V&A) component of the national communications which Parties submit to the secretariat of the United Nations Framework Convention on Climate Change (UNFCCC). Namely, this chapter provides a brief overview of potential climate change impacts on critical water resource elements (in the appendices), as well as guidance on the key tools and methods available to support vulnerability assessment and adaptation planning. The chapter is structured as follows: section 6.2 presents a brief summary of water resource impacts; section 6.3 addresses methods and tools; and section 6.4 presents data requirements and sources.

Other chapters in the training materials contain important information for conducting climate change V&A assessments for water resources. Specifically:

- Chapter 2 discusses V&A frameworks;
- Chapter 3 addresses baseline socioeconomic scenarios. As noted in this chapter, water resources can change substantially over the coming decades;
- Chapter 4 is on climate change scenarios;
- Chapters 5, 7 and 8 are on coastal resources, agriculture and human health, respectively. There will be important interactions with water resources and all of these sectors;
- Chapter 9 discusses integration across sectors as well as adaptation, mainstreaming, monitoring and evaluation;
- Chapter 10 is on communication of V&A results;
- Appendix 6-1 discusses drivers of climate change impacts on the water resources sector;
- Appendix 6-2 briefly summarizes the literature on climate change impacts on the sector;

- Appendix 6-3 presents options for water resources adaptation.

Several key resources provide a thorough review of water resource management issues within the context of climate change. These include:

- The Fourth and Fifth Assessment Reports (AR4 and AR5) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007b, 2013)[1];
- IPCC Technical Paper, *Climate Change and Water* (Bates et al., 2008), written in response to suggestions by the World Climate Programme – *Water, the Dialogue on Water*;
- United Nations Development Programme (UNDP) Cap Net (2009) training manual, *IWRM as a Tool for Adaptation to Climate Change*[2];
- United Nations Environment Programme (UNEP) (2012) *Integrated Water Resources Management Planning Approach for Small Island Developing States*.

This chapter draws predominantly on content from these resources and provides links to additional technical information where required.

6.2. Summary of water cycle impacts

The appendices summarize a key set of expected water cycle changes as a result of climate change, which water managers and planners will need to assess and adapt to, as they plan their water resources over the coming decades. The main issues and impacts of each of the expected hydrologic changes are summarized in Table 6-1 below.

Table 6-1
Summary of the expected water cycle changes described by the Fifth Assessment Report towards the end of the twenty-first century

Component	Key issues and impacts
Evaporation and precipitation	• Changes in evaporation exceed precipitation (less run-off and recharge) in central North America, Central America, northern South America, southern Chilean Coast, southern Africa, western Europe, the Mediterranean and south-central Asia • Precipitation exceeds evaporation (more run-off and recharge) in the high latitudes, eastern North America, northwest South America, central Africa, India and East Asia
Groundwater	• Surface water recharge is strongly tied to groundwater variability in unconfined aquifers • Increased abstraction from population growth and reduced surface water availability could result in declining groundwater levels, particular in areas experiencing warming and precipitation deficits

[1] Available at: <http://www.ipcc.ch/>. See both the Working Group I report on the physical science basis of potential future changes to the hydrological cycle and the Working Group II report, chapter 3, "Freshwater Resources and their Management".
[2] Available at: <http://www.gwp.org/Global/GWP-CACENA_Files/en/pdf/capnet-adapt-to-climate-manual_en.pdf/>.

Component	Key issues and impacts
Stream flow	• Significant regional variation range in run-off and stream flows; stream flows in high-latitude rivers increase • Increased precipitation intensity leads to greater floods and can also exacerbate droughts
Coastal zones	• Increased inundation and coastal flooding causing salinization of groundwater and estuaries • Changes in the timing and volume of freshwater run-off affecting salinity, sediment and nutrient availability • Changes in water quality may come as a result of the impact of sea level rise on storm-water drainage operations and sewage disposal in coastal areas • Changes to the zonation of plant and animal species as well as the availability of freshwater for human use as a result of salinity advancing upstream due to decreased stream flow
Water quality	• Higher water temperatures may degrade water quality, which can be made worse by the presence of pollution • Changes in flooding and droughts may affect water quality through sediments, nutrients, dissolved organic carbon, pathogens, pesticides and salt • Sea level rise is projected to extend areas of salinization in groundwater and estuaries
Demand, supply and sanitation	• Climate change will likely add further stress to water service issues, including supply, demand and governance

Source: IPCC, 2013.

Working Group II of the IPCC AR5 notes that high latitude land masses are likely to experience greater amounts of precipitation due to the additional water-carrying capacity of the warmer troposphere. Many mid-latitude subtropical arid and semi-arid regions will likely experience less precipitation. The largest projected changes in precipitation occur during the winter over northern Eurasia and North America.

The Working Group of the IPCC AR5 provides a plot of the parameter ‘Evaporation minus precipitation,’ which is a useful metric for integrating the combined impacts of changing precipitation, humidity and temperature; and thus a good indicator of increases or decreases in surface water availability and groundwater recharge.

6.3. Assessment: methods, tools and data requirements

Climate change will challenge existing water management practices, especially in countries that have less experience in incorporating uncertainty into water planning and lower levels of financial and institutional support. The current challenge is to incorporate climate change scenarios, including their uncertainties, along with the other types of uncertainty usually addressed in water planning processes.

Climate change analysis in water planning is often supported through the use of hydrologic simulation to study the effect of a changing climate on water supply and demand through analysis of the hydrologic cycle. On the supply side, this includes the physical processes of rainfall run-off and stream flow generation, snow accumulation and melt (where important), groundwater recharge and other aspects. On the demand side, the analysis can include understanding the temporal and spatial variability in water demand from crops and plants owing to soil moisture deficits or water use for municipal and industrial uses.

Hydrologic models capture the physical mechanisms of run-off production across the landscape by: characterizing precipitation on to the land surface, either directly or through snowmelt; and by the partitioning of that water into evapotranspiration, run-off to the river network and recharge to groundwater systems. Water planning and evaluation models then use these water fluxes to determine reservoir management and water delivery strategies, often accommodating multiple uses and objectives, which can include water supply, flood protection, environmental stewardship and socioeconomic objectives. These water systems are managed within regulatory environments that vary considerably according to local institutional capacity, cultural practices and values and other considerations.

6.3.1. General considerations

Water resource assessments of potential climate change impacts and adaptations have generally approached the problem from one of two perspectives – either *top-down* or *bottom-up* (see Chapter 2 for more information on V&A frameworks, including top-down and bottom-up). The approach taken is often based on the needs or requirements of the study.

A ***top-down approach*** establishes the scientific credibility of human-induced climate warming, develops future climate projections to be used at the regional level and then imposes those potential changes on water resource systems to assess, for example, changes in stream flow or water system yield. This approach has largely emerged out of the need to satisfy broad communication needs relating to potential climate change impacts and adaptation options in the water resources sector.

For example, under the UNFCCC national communication process, countries often use a top-down approach to evaluate the possible impacts of climate change on stream flow, water system yield or other metrics at regional and national levels. The advantages of a top-down approach include its relative ease of implementation, its straightforward analysis process and the transparency of results. Drawbacks include the fact that it might not address the unique needs of a region, can become mired in the uncertainty of the future climate projections and does not lend itself to exploration of tangible adaptation options.

Conversely, a ***bottom-up approach*** often emerges from the recognition that a water system is unique and climate change impacts and adaptation options have to be identified for that particular system. A bottom-up approach is often undertaken, for example, by urban water supply managers or a river basin commission, both of which are responsible for a particular water system.

The bottom-up approach is well suited to follow select V&A frameworks outlined in Chapter 2, such as the UNDP six-step approach (UNDP, 2010). The bottom-up analysis begins by specifying the water systems’ most critical vulnerabilities and water resource management challenges; identifying the causes for those vulnerabilities; and suggesting how climate change, climate variability and climate extremes may or may not exacerbate those vulnerabilities. From this, an analytical process is undertaken to address and evaluate the vulnerability in the face of the climatic uncertainty (e.g., a precautionary approach or to achieve a robust outcome). Similar to top-down, the bottom-up approach can make use of climate projections.

Some advantages of a bottom-up approach include the fact that it can address the specific needs and issues of the local or regional water system, the vulnerabilities are uniquely identified and adaptation options can be designed to meet the specific needs of the water system. The drawbacks of the approach are that it can require greater resources and time to complete the analytical and stakeholder process.

This chapter focuses on frameworks that follow the bottom-up process.

Integrated water resource management (IWRM), is one such framework. It is identified as an effective approach to assess vulnerabilities and explore adaptation options in the context of a changing climate and an evolving regulatory environment. The IWRM approach is outlined in the following section.

6.3.2. Integrated water resource management as a vulnerability and adaptation framework

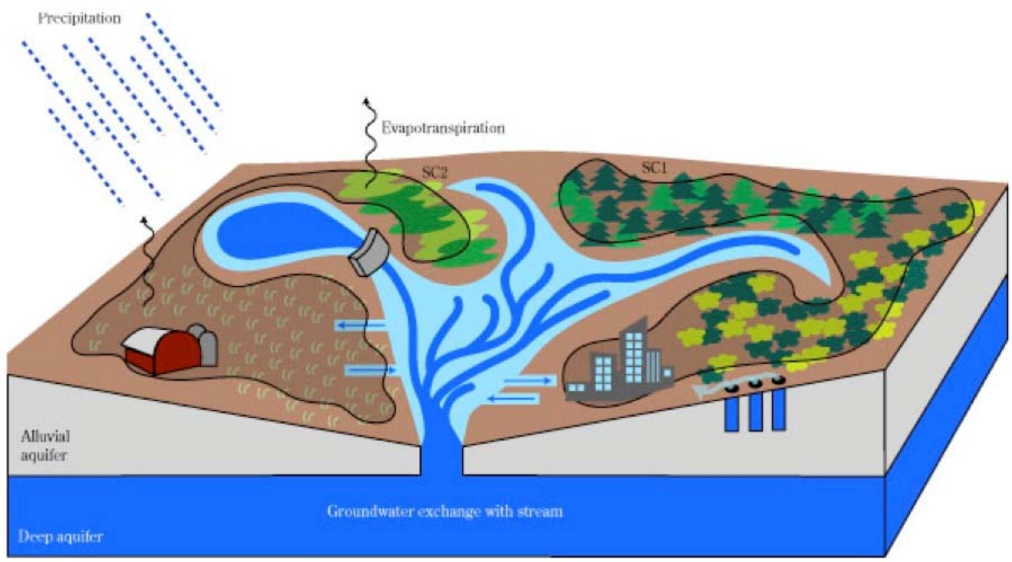
IWRM is a planning and management framework that considers a range of supply-side and demand-side water resources processes and actions and incorporates stakeholder participation in decision-making. The IWRM framework encompasses analyses of the costs and benefits of demand-side and supply-side management options. It also promotes an open and participatory decision-making process, the development of water resource alternatives that incorporate consideration of community values and environmental issues which may be impacted by the ultimate decision, and the recognition of the multiple institutions concerned with water resources and the competing policy goals among them.

The Global Water Partnership[3] defines IWRM as a process that promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems. The IWRM framework is meant to be comprehensive in representing all aspects of the water system, as represented in Figure 6-1, where both climatically driven supply-side elements are linked to demand and the managed water system.

The IWRM framework includes planning methods and approaches that identify the most efficient means of achieving goals while considering the costs of project impacts on other community objectives and environmental management goals. These planning methods specifically require evaluation of all benefits and costs, including avoided costs and life-cycle costs (AWWA, 2001).

[3] See <http://www.gwp.org/The-Challenge/What-is-IWRM/>.

Figure 6-1
The interface between the natural watershed and managed systems



6.3.3. Robust decision-making as an integrated water resource management method

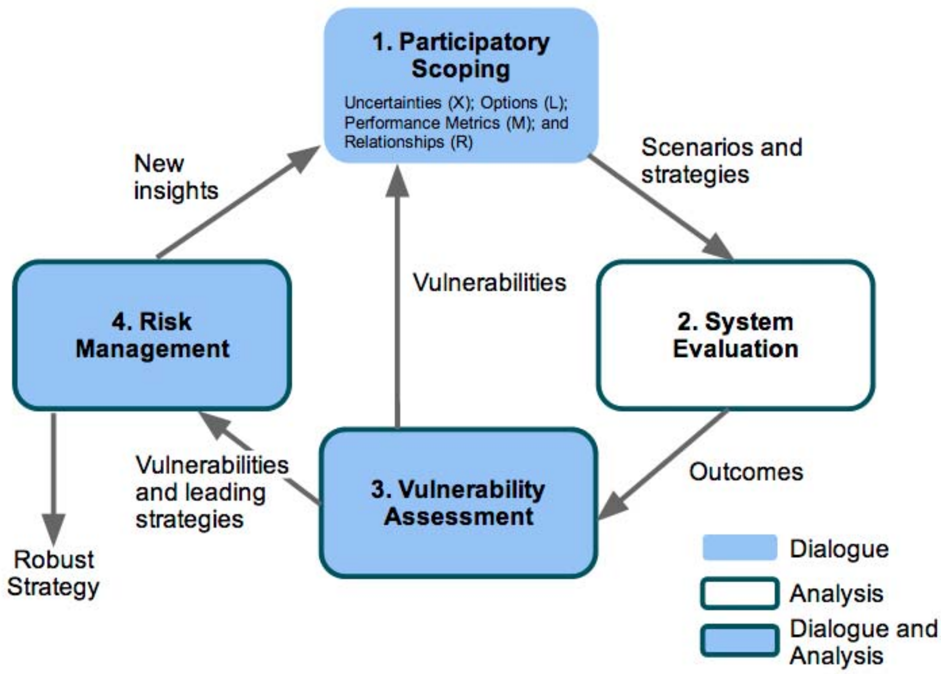
As a framework, IWRM does not provide specific guidance for how to assess uncertainty or evaluate risk under conditions of deep uncertainty, which pervade long-term climate adaptation planning efforts. One method of IWRM – robust decision-making (RDM) (Groves et al., 2008; WaterRF, 2013; see also Chapter 9) – is designed to address ‘deep uncertainty’ planning challenges by explicitly using iteration to support an exploratory analysis of vulnerabilities and reducing vulnerabilities through robust risk management strategies. The RDM approach is based on a few central principles and is summarized in Figure 6-2 and as follows:

1. ***Supports an iterative and participatory dialogue.*** Broad participation and strong leadership are imperatives throughout the process. The process should develop analytic results that support dialogue with stakeholders and decision makers, which in turn provides new insights into the analysis that should be performed next (see Box 6-1 below);
2. ***Identifies a wide range of uncertainties and plausible scenarios.*** Climate change is only one of the many uncertain factors that affect water utilities. The many combinations of different uncertainties could lead to a wide array of plausible scenarios that should be explored as much as possible;
3. ***Explores a spectrum of possible future climates.*** Climate science, although still maturing, is informative. Climate projections based on climate model outputs, regional climate modelling experiments, downscaling, climate narratives, etc., should be used to explore a full range of future climates;
4. ***Identifies key vulnerabilities.*** From simple conceptual models to complex computer models, the process should help to illuminate vulnerability of the

resource to climate and other uncertainties. This information is the best guide to the development of adaptation strategies;

5. ***Seeks robust, adaptive strategies.*** Given the large uncertainty of future climate and other factors, decision science methods should be brought to bear that can be used to develop adaptation strategies for water utilities that are robust across an array of performance metrics. Robust strategies in this context would be those that will achieve goals across a broad range of future scenarios rather than those that are optimal under a single set of assumptions about the future. A variety of different performance metrics and methods can be used, ranging from simple approaches such as benefit-cost analysis to more complicated algorithms that account for competing and multiple interests, such as multi-criteria decision analysis.

Figure 6-2
The robust decision-making approach for water planning



Source: Figure modified from Lempert, Popper and Bankdes, 2003.

RDM is different from traditional planning approaches in some important ways. First, RDM de-emphasizes the sometimes arduous development of a few choice scenarios to reflect uncertainty. Rather, it relies on computer simulation models to evaluate large ensembles of scenarios and, from the analytic results, identifies a small set of scenarios that are relevant to risk management decisions. Second, because future climate and other long-term trends are so uncertain and agencies must make definitive choices to prepare for the next 50 to 100 years, the RDM approach does not try to identify optimal strategies. Instead, it focuses on strategies that seek to be robust, strategies that are shown to perform sufficiently well under a wide range of alternative assumptions about the future. Third, rather than analytically identifying a single 'preferred alternative', RDM highlights the trade-offs among strategies. This information then informs a dialogue about choices that necessarily requires the inclusion of subjective information about how severe risks might be and the willingness to invest to mitigate these risks.

Box 6-1
Participatory scoping using XLRM

The dialogue step in RDM brings stakeholders, planners and decision makers together, in a structured analysis process, to identify the key uncertainties that confront them and the metrics that describe how well future goals of the water system would perform.

The 'XLRM matrix' is a useful tool for structuring dialogue about these elements. The matrix can be thought of simply as four boxes that document, for an RDM analysis, the uncertain factors or uncertainties (Xs) that define scenarios, the management decisions or options or levers (Ls) that comprise alternative strategies, the performance metrics or goals (Ms) used to describe outcomes and the relationships or models (Rs) used to simulate a water management system (Figure 6-3). This step can also be used to define alternative adaptation decisions, such as investments or programmes, and select or develop the relationships or models that will be used to estimate how the system will perform in the future.

For example stakeholders may express concern that future extended droughts (an "X") will lead to reductions in available surface supplies for irrigation (an "M"). They may follow up by stating that they would need to develop additional groundwater pumping capacity (an "L") to enable them to replace surface supplies with groundwater. They may finally express concern that pumping costs (an "M") will be higher than the costs of diverting surface flows, particularly if groundwater levels decline with increased use (an "R"). These reasonable conditions and concerns are articulated, disaggregated and recorded in an XLRM matrix as shown in Figure 6-3.

Figure 6-3
The XLRM matrix reflecting stakeholder concerns

Uncertainties (X)	**Decisions/options/levers (L)**
Climate conditions Historical conditions Extended drought	Current infrastructure Expanded groundwater pumping capacity
Relationships or models (R)	**Performance metrics/goals (M)**
Surface/groundwater hydrology model	Available surface supply Costs of obtaining supply

Source: Lempert, Popper and Bankdes, 2003.

6.3.4. Hydrologic and water management models

IWRM methods such as RDM rely on models of the hydrologic and managed water systems. Hydrologic models simulate physical processes, including precipitation, evapotranspiration, catchment run-off, infiltration, stream flow and groundwater flow (see Figure 6-1). In managed systems, analysts must also account for the operation of hydraulic structures, such as dams and diversions, as well as institutional factors that govern the allocation of water between competing demands, including consumptive demand for agricultural or urban water supply or non-consumptive demands for hydropower generation or ecosystem protection. Because water quality will also change with climate change, special attention should be paid to water quality changes. Such changes may result in increased restrictions on water withdrawals to maintain water quality and ecosystem health. Changes in each of these elements can influence the ultimate impacts of climate change on water resources.

Although different hydrologic models can yield different estimates of stream flow, groundwater recharge, water quality results and so on (Boorman and Sefton, 1997; Beven, 2004), their differences have historically been small compared with the uncertainties attributed to climate change reflected in the differences among the outputs of global climate models (GCMs). The chain of effects, however, from climate to hydrologic response, to water resource systems, to the actual impacts on water supply, power generation, navigation, water quality and so on, will depend on many factors, each with a different level of uncertainty that must be addressed transparently in impact assessments (Chapter 4 addresses options for creating climate change scenarios).

A number of models and tools are available for integrated water resources assessment, planning and management that can be divided into two broad categories:

1. Models that simulate physical hydrologic processes within a catchment. These models use mathematical constructs of the hydrologic cycle to make estimates of catchment run-off, stream flow, groundwater recharge, flood levels, and so on, based upon input parameters including catchment characteristics and meteorological data. These models typically require a significant amount of observed data in order to achieve adequate model calibration and validation;
2. Water management models include those that represent the temporal and spatial availability of water between different and often competing uses, within and across river basins and/or politically defined areas. These models include representations of important water infrastructure such as reservoirs, diversions, pipelines, demand centres and so on.

A range of modelling packages are available that incorporate both physical process simulation as well as water management issues. Models vary from freely available, simple one-dimensional models to the more advanced (and expensive) three-dimensional simulation packages. Commercial models are available for application in water resource management; many of these models are summarized in the UNFCCC Compendium of methods and tools to evaluate impacts of, and vulnerability to, climate change[4]. There are also summaries of the various methods and tools available in the Global Water Partnership Toolbox on Integrated Water Resource Management[5]. A selection of these models is summarized in Table 6-2.

[4] The Compendium is available for download at: <https://unfccc.int/files/adaptation/methodologies_for/vulnerability_and_adaptation/application/pdf/consolidated_version_updated_021204.pdf>.
[5] Available at: <http://gwptoolbox.org/>.

Table 6-2
Selected hydrologic and water system models

Model	Source	Licensing and training	Description	Link*
WEAP (b)	Stockholm Environment Institute (SEI)	Free to developing counties Regular training workshops	The Water Evaluation and Planning (WEAP) system is a surface and groundwater resources simulation tool based on water-balance accounting principles, which can test alternative sets of conditions for both supply and demand.	<http://www.weap21.org/>
MODSIM-DSS (w)	Colorado State University	Free Periodic training workshops	MODSIM-DSS, a generalized river network flow model, can simulate the complex physical, institutional and hydrological characteristics of river basin management, including water rights.	<http://modsim.engr.colostate.edu/>
RiverWare (w)	Center for Advanced Decision Support for Water and Environmental Systems, University of Colorado	License required; technical support available	RiverWare is a reservoir and river basin simulation and optimization model used to evaluate operational policy, system optimization, water accounting, water rights administration and long-term resource planning.	<http://www.riverware.org/>
WaterWare (b)	Environmental software and services	License required; completely web-based	WaterWare is an integrated, model-based information and decision support system (DSS) for water resources management.	<http://www.ess.co.at/WATERWARE/>
SWAT (h)	United States Department of Agriculture (USDA)	Free Regular training workshops	SWAT (Soil and Water Assessment Tool) is a river basin scale model designed to quantify the impact of land management practices in large complex watersheds.	<http://swatmodel.tamu.edu/>
HEC-HMS, HEC-RAS (River Analysis System), HEC-ResSim (Reservoir System Simulation) (b)	United States Army Corps of Engineers (USACE)	Free Technical support only for USACE customers Regular training workshops	The suite of HEC-HMS (Hydrologic Engineering Center-Hydrologic Modeling System) models are designed to perform a multitude of water-resource tasks, including: precipitation/run-off processes of dendritic watershed systems; quantify one-dimensional steady flow, unsteady flow and sediment; and simulate reservoir operations at one or more reservoirs.	<https://www.hec.usace.army.mil/>

Model	Source	Licensing and training	Description	Link*
PRMS (h)	United States Geological Survey (USGS)	Free Training workshops available through USGS	The PRMS (Precipitation Runoff Modeling System) is a physical process watershed model developed to evaluate the effects of various combinations of precipitation, climate and land use on watershed response (Markstom et al., 2015).	<http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/PRMS.html>
MIKE-SHE (h) MIKE Basin (w) MIKE21 (h)	Danish Hydraulic Institute (DHI)	License required Regular training workshops globally	MIKE-SHE is an integrated hydrological modelling system that simulates water flow in the land-based phase of the hydrological cycle. MIKE BASIN is a tool for addressing water allocation, conjunctive use, reservoir operation or water quality issues. MIKE21 is a two-dimensional model design to simulate coastal and estuarine hydrodynamics, sediment transport, waves and ecological systems.	<http://mikebydhi.com/Products>
HYMOS (b)	Deltares (Dutch Institute for National and International Delta Issues)	License required Regular training workshops	HYMOS (hydrologic data management) is an information system for water resources management in general. It includes all data storage and processing requirements for analysis, planning, design and operation of water management systems.	<http://publicwiki.deltares.nl/display/HYMOS/>
Delft3D (h)	Deltares	License required Regular training workshops	Delft3D is a three-dimensional model designed to investigate hydrodynamics, sediment transport and morphology and water quality for fluvial, estuarine and coastal environments.	<https://www.deltares.nl/en/software/delft3d-4-suite/>
Aquarius (w)	USDA	Free Seminars held within the United States	Aquarius is an analysis framework depicting the temporal and spatial allocation of water flows among competing traditional and non-traditional water uses in a river basin.	<https://www.fs.fed.us/rm/value/aquarius.html>
RIBASIM (w)	Deltares	License required Regular training workshops	RIBASIM is a generic model package for simulating the behaviour of river basins under various hydrological conditions for surface and groundwater systems.	<https://www.deltares.nl/en/software/ribasim/>

* Websites were accessed in June 2021.
Notes: Model types are indicated as being hydrologic (h), a water management system (w), or both (b).

Each of the above models can be used in different situations to support an IWRM approach within a climate change context. A range of factors, including cost, technical capacity, access to training resources, the desired quality of the models' output and input data requirements, will determine the use of a particular model. A few guidance resources are shown in Table 6-3, which are useful when water resource stakeholder groups are undergoing an IWRM process that includes the consideration of climate change.

Table 6-3
Additional resources

Resource	**Source**	**Description**	**Link**
IWRM as a Tool for Adaptation to Climate Change: Training Manual and Facilitator's Guide	UNDP-Cap Net	Training material providing introduction to IWRM as an instrument for adaptation to climate change. Also provides links to national-level resource centres that provide education, training, research and consultancy services in the field of water.	<http://www.cap-net.org>
weADAPT	SEI	weADAPT is an online 'open space' on climate adaptation issues (including the synergies between adaptation and mitigation), which allows practitioners, researchers and policymakers to access credible, high-quality information and to share experiences and lessons learned.	<https://weadapt.org/>
How to integrate climate change adaptation into national-level policy and planning in the water sector	Tearfund International	A practical guidebook for developing country government to integrate resilience and adaptation into their water sectors.	<http://tilz.tearfund.org>
How to undertake an RDM analysis process in the water resources sector	The Water Research Foundation and RAND Corporation	The Water Research Foundation has supported climate change research for the drinking water industry and provides reports and information on methods and approaches. The RAND Corporation aims for interdisciplinary and quantitative problem solving by translating theoretical concepts from formal economics and the physical sciences into novel applications in other areas, using applied science and operations research.	<http://WaterRF.org> <http://Rand.org>

As outlined in Table 6-2, there are a number of water resource management models that can be used to support the development of national communications. A useful tool that has been used in national communications and provides an integrated approach to water resource planning is the WEAP21 decision support system (DSS) (see Box 6-2 below). Generally, the other models outlined in Table 6-2 are used to generate specific data for one component of water resource modelling.

Box 6-2
The WEAP decision support model

The WEAP DSS is a software tool that takes an integrated approach to water resources planning. It has been through a series of developments over its 20-year history. The WEAP model attempts to address the gap between water management and watershed hydrology, and the requirements that an effective integrated water resources model be useful, easy to use, affordable and readily available to the broad water resource community. WEAP integrates a range of physical hydrologic processes with the management of demands and installed infrastructure in a coherent manner. It allows for multiple scenario analysis, including alternative climate projections and changing anthropogenic stressors, such as land-use variations, changes in municipal and industrial demands, alternative operating rules and points of diversion changes. WEAP's strength is in addressing water planning and resource allocation problems and issues and, importantly, it is not designed to be a detailed water operations model that might be used to optimize hydropower based on hydrologic forecasts, for example.

The management system in the WEAP DSS is described by a user-defined demand priority and supply preference set for each demand site used to construct an optimization routine that allocates available supplies (Yates et al., 2005a, 2005b). Demands are defined by the user, but typically include municipal and industrial demand, irrigated portions of sub-catchments and environmental flow requirements. Demand analysis in WEAP that is not covered by the evapotranspiration-based irrigation demand follows a disaggregated, end use based approach for determining water requirements at each demand node. Economic, demographic and water use information is used to construct alternative scenarios that examine how total and disaggregated consumption of water evolve over time. These demand scenarios are computed in WEAP and applied deterministically to a linear program-based allocation algorithm. Demand analysis is the starting point for conducting integrated water planning analysis because all supply and resource calculations in WEAP are driven by the optimization routine that determines the final delivery to each demand node, based on the priorities specified by the user.

Importantly, there is a suite of online support and training materials, including tutorials in English, Chinese, Spanish, French and Farsi and an online discussion forum (in English). There is also an extensive publication list covering its application in a range of water planning contexts, including specific climate change impact and adaptation studies, many of which can be downloaded from the WEAP website[a]. There are also regular training courses and a network of university departments that include WEAP in their curriculum, and as a result have in-country expertise in the software.

[a] See: <http://www.WEAP21.org/>.
Source: Yates et al., 2005a, 2005b.

6.4. Data requirements and sources

Water resource planning models require data on water demand and water supply (see Table 6-4). Water demand information usually needs to come from local sources – including water use per capita, and domestic rates and industrial and commercial water use rates. Common water-use rates can be obtained from national water planning agencies or from the literature, if necessary. Irrigation demands can be determined from local knowledge regarding cropping and other agricultural practices and the climate from national agricultural and/or resource management departments. Data on demand for cooling water for thermal power plants and mainstream demands for navigation, recreation and hydropower are usually available from users. Data on ecosystem demand may be available from environmental agencies.

Table 6-4
Sources of data on water resources

Source	Description	Link*
AQUASTAT (FAO's Global Information System on Water and Agriculture)	Provides comprehensive information on the state of agricultural water management across the world, with emphasis on developing countries and countries in transition. Includes database of infrastructure, including dams, water use, irrigation, etc.	<http://www.fao.org/nr/water/aquastat>
The World's Water (Pacific Institute)	Provides information, data and relevant links to information on the world's freshwater resources.	<http://www.worldwater.org>
United Nations water statistics	Provides statistics on key indicators for the water sector that can be used at global, regional and national levels.	<https://www.unwater.org/water-facts/>
World Bank water data and research	Provides country level statistics and data about water sector and a broad range of other indicators.	<http://www.worldbank.org/en/topic/water>
United Nations Statistics Division (indicators on water supply and sanitation)	Provides up-to-date statistics on water supply and sanitation and other social indicators at a national level.	<http://unstats.un.org/unsd>
United Nations Environment Programme (UNEP) Environmental Data Explorer	Provides access to the datasets used by UNEP and its partners in its integrated environmental assessments.	<http://geodata.grid.unep.ch>
University of New Hampshire EOS-EARTHDATA	Provides free, customized Earth science data.	<http://eos-earthdata.sr.unh.edu/data/>
The Global Energy and Water Exchanges (GEWEX) project	An integrated programme of research, observations and science activities about predicting global and regional climate change.	<http://www.gewex.org/>

Source	Description	Link*
CEOS International Directory Network (IDN)	Provides descriptions of Earth science datasets and services relevant to global change research.	<https://idn.ceos.org/>
Global Hydrology Resource Center (GHRC)	Provides both historical and current Earth science data, information and products from satellite, airborne and surface-based instruments.	<https://ghrc.nsstc.nasa.gov/home/>
Global Runoff Data Centre (GRDC)	Collects and disseminates river discharge data on a global regional or catchment scale under the auspices of the World Meteorological Organization (WMO).	<http://www.bafg.de/GRDC>
International Groundwater Resources Assessment Centre (IGRAC)	Disseminates groundwater information and knowledge with the development of a global groundwater information system.	<http://www.un-igrac.org/>
National Centers for Environmental Information (NCEI)	The world's largest archive of weather data.	<http://www.ncdc.noaa.gov/>
Climatic Research Unit (CRU)	CRU at the University of East Anglia provides global, high-resolution historical climate datasets.	<http://www.cru.uea.ac.uk/>
Terrestrial Hydrology Group (Princeton University)	Provides climate data models and related studies, including Global Meteorological Forcing Dataset for land surface modelling.	<http://hydrology.princeton.edu>
World Hydrological Cycle Observing System (WHYCOS) WMO	Aims to improve basic observation activities to strengthen international cooperation and promote free exchange of data in the field of hydrology.	<http://www.whycos.org/>

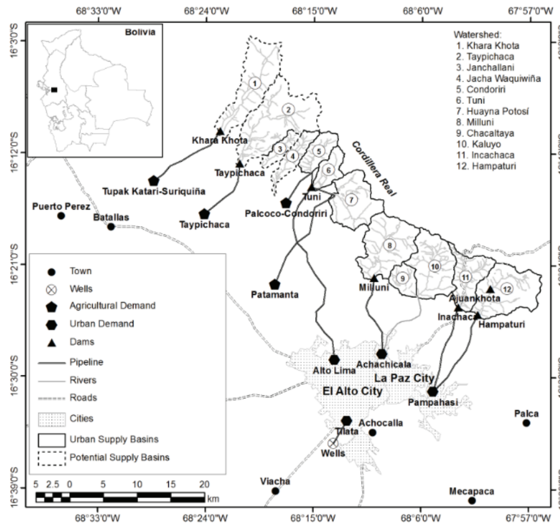
* Websites were accessed in June 2021.

Water supply data can be given as time series of river flows or groundwater availability (remembering that in many cases, surface water and groundwater systems are interconnected) or generated from physical hydrology or watershed models based on land use, topography and geology, and on climate data, such as precipitation, temperature, humidity and wind speed. Modelling usually requires a time series of run-off and groundwater availability with minimum time steps of one month. Once natural flows are determined, adjustments in availability must be made based on water infrastructure such as reservoirs, wells, transmission networks and water treatment plants.

Box 6-3 briefly summarizes an example of an end-to-end climate change V&A study of Bolivia that made use of the IWRM framework and employed RDS and XLRM process.

Box 6-3
Robust decision support in Bolivia

La Paz and El Alto are two cities in the Bolivian Altiplano of the high Andes, facing prolonged water supply problems. As one of South America's poorest populations, the communities of El Alto and La Paz have been acutely affected by a lack of access to water and sewage services. In addition, these neighbouring cities have become some of the fastest growing in Latin America, as indigenous peoples have left rural areas to seek to improve their livelihoods. The cities' populations have grown at a rate of more than 10% annually, with the land area of El Alto expanding even more rapidly, spreading into the countryside to the south and west.



GCMs suggest that the region will see temperatures rise by 2°C by 2050, which would lead to the disappearance of many small glaciers and the dramatic shrinking of others. Glaciers provide about 25% of water annually for El Alto and La Paz; therefore, glacier loss will have a considerable impact that will be felt particularly during the dry season, when glacial water provides the majority of urban water. Glaciers and mountain water systems also support agriculture, power generation and natural ecosystems throughout the region. It also appears that more rainfall will not compensate for glacial melt: although some climate models suggest an increase in rainfall of up to 4%, most suggest a reduction of up to 10% by 2050.

With climate change and other factors, the two cities face great challenges in meeting the demands of a growing population. The XLRM framework served to organize a IWRM process, where the external factors (i.e., the 'X') included future climate change, population growth, per capita water consumption, changes in priorities distribution between urban and agricultural areas and growth of the agricultural frontier. A consortium of Bolivian government staff and academic researchers, advised by staff from the National Center for Atmospheric Research (NCAR) and the Stockholm Environment Institute (SEA), identified a set of strategies or levers (i.e., the 'L'), including new water storage reservoirs, wetlands conservation, reducing losses in irrigation systems and reducing losses in urban systems. The research team applied the WEAP model (i.e., the 'R') of the water systems to analyse how various external factors (X) and management strategies (L) interacted. They also applied a set of performance measures (i.e., the 'M') to compare the effectiveness of different strategies. The dynamics of stream flow, glacier area and resulting water supply were used to evaluate water demand coverage for municipal and agriculture use, the volume of water stored in reservoirs and overall system reliability, vulnerability and resilience.

Box 6-3 (cont.)
Robust decision support in Bolivia

In the most pessimistic of climate change scenarios, the new water sources proposed for the region could see reductions of about 30%. Other conservation and recycling methods will be essential for El Alto and La Paz to build the resilience of its water systems to climate change.

Source: Escobar et al., 2013.

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Appendix 6-1: Drivers of change

The Intergovernmental Panel on Climate Change (IPCC) Technical Paper, *Climate Change and Water* (Bates et al., 2008), provides a comprehensive summary of projected changes in climate as they relate to water, which is summarized in this appendix (excluding sea level, which is addressed in Chapter 5).

Precipitation (including extremes and variability) and water vapour

In the Fourth Assessment Report (AR4) of the IPCC, Working Group I summarized that climate change will alter the hydrologic cycle, leading to altered patterns of precipitation and run-off. In broad terms, the IPCC concluded that over the 21st century, globally averaged mean water vapour, evaporation and precipitation would increase, with:

- Increased precipitation generally in the areas of regional tropical precipitation maxima (such as the monsoon regimes, and the tropical Pacific in particular) and at high latitudes;
- General decreases in precipitation in the sub-tropics.

Importantly, the IPCC concluded that these patterns continue to be observed in recent trends (see Box 6-4). The overall global patterns of potential future precipitation and other water cycle changes are shown in Figure 6-4.

Box 6-4
Changes in precipitation patterns in Asia

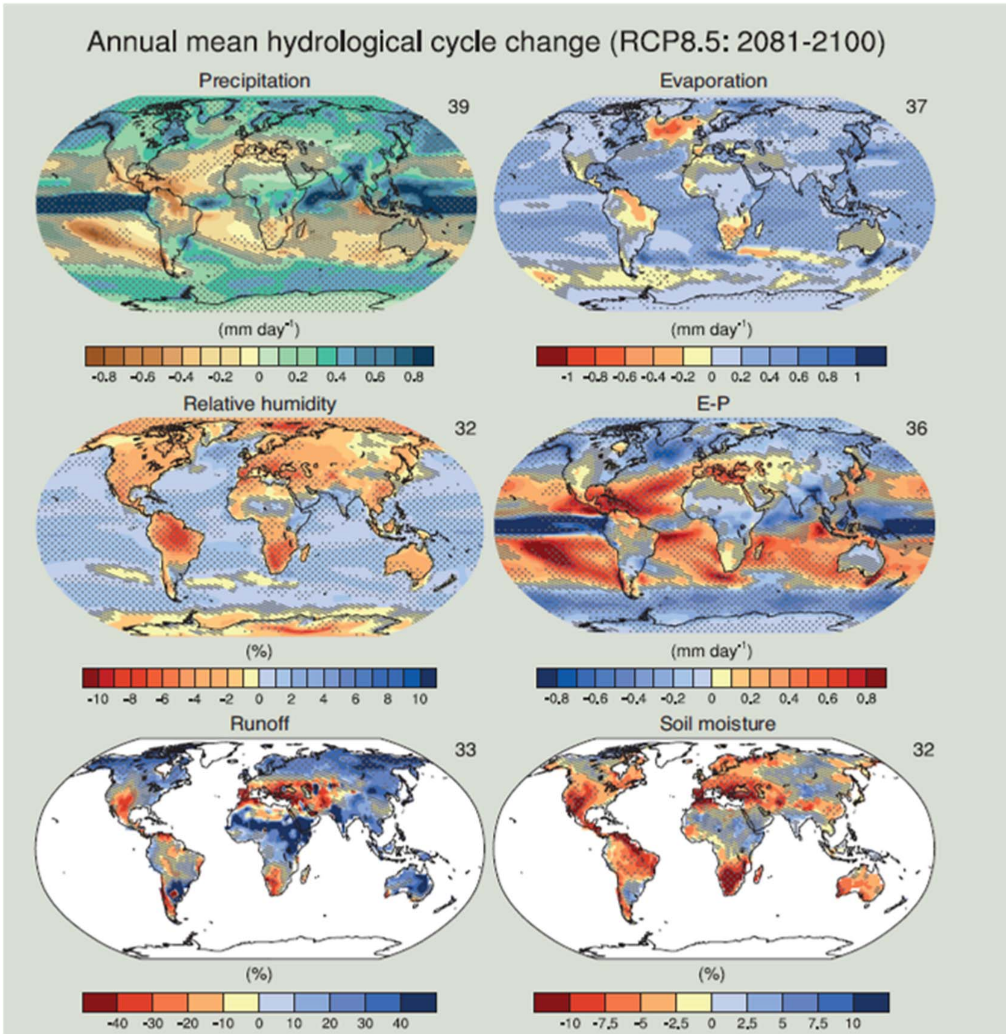
A study by the United States Agency for International Development (USAID) in 2010 reported that annual precipitation in China has been declining since 1965, with stronger summer monsoons during globally warmer years, and drier monsoons during globally cooler years. In Mongolia, the reported rainfall patterns have been more seasonally variable, with autumn and winter precipitation increasing by 4–9% over the past 60 years and spring and summer precipitation decreasing by 7.5–10%. In India, extreme rains during the summer monsoon were reported to have increased in the north-west while the number of rainy days along the east coast has decreased.

Climate change has also exacerbated droughts associated with El Niño events, of which there has already been an increased incidence in Indonesia, Laos, the Philippines, Vietnam, the Solomon Islands and the Marshall Islands. The USAID report noted that low-lying coastal areas throughout the region are highly vulnerable to flood disasters.

Source: Adapted from USAID, 2010.

All climate model simulations show complex patterns of precipitation change, with some regions receiving less and others receiving more precipitation than they do now. Changes in circulation patterns, driven by global factors and also the complexities of local climate systems, will be critically important in determining changes in local and regional precipitation patterns.

Figure 6-4
Annual mean changes in precipitation, evaporation, relative humidity, E – P, run-off and soil moisture for 2081–2100 relative to 1986–2005 under the representative concentration pathway RCP8.5



Notes: The number of Coupled Model Intercomparison Project Phase 5 (CMIP5) models to calculate the multi-model mean is indicated in the upper right corner of each panel. Hatching indicates regions where the multi-model mean change is less than one standard deviation of internal variability. Stippling indicates regions where the multi-model mean change is greater than two standard deviations of internal variability and where 90% of models agree on the sign of change.
Abbreviations: E = evaporation, P = precipitation.

In addition to changes in mean annual-average precipitation worldwide, there are likely to be changes in the frequency and distribution of extreme precipitation events. AR4 concluded that:

- It is very likely that heavy precipitation events will become more frequent;
- It is likely that future tropical cyclones will be become more intense, resulting in more intense rainfall events;
- The intensity of precipitation events is projected to increase, particularly in tropical and high-latitude areas that experience increases in mean precipitation;

- There is a tendency for drying in mid-continental areas during summer, indicating a greater risk of droughts in these regions;
- In most tropical and mid- and high-latitude areas, extreme precipitation increases more than mean precipitation;
- Extra tropical storm tracks are projected to move pole-ward;
- It is not yet possible to make definitive projection of trends in future El Niño Southern Oscillation (ENSO) variability due to climate change.

It is important to stress that the IPCC found substantial regional variation in future patterns of extreme precipitation events and that there is a lack of ability to project future changes due to both a lack of observed climatological data and a consensus among modelling study results, because the GCM output suggest a large range of future variability.

Consequently, to ensure that regional-level scenarios of precipitation changes are captured effectively in water resource planning aspects of national communications, careful selection of a scenario development process (outlined in Chapter 4) is required.

Snow and land ice

As summarized in Bates et al. (2008, p. 27), AR4 concluded that:

> *As the climate warms, snow cover is projected to contract and decrease, and glaciers and ice caps to lose mass, as a consequence of the increase in summer melting being greater than the increase in winter snowfall. Widespread increases in thaw depth over much of the permafrost regions are projected to occur in response to warming.*

Climate models project widespread reductions in snow cover throughout the twenty-first century, which are not offset by some projected increases in snowfall at higher altitudes. These are significant for high-latitude and mountain systems and also for snow- and ice-fed river systems.

Evapotranspiration

AR4 outlined that potential evaporation is projected to increase in nearly all parts of the world. This is due to an increase in the water-holding capacity of the atmosphere in the future with higher temperatures, while relative humidity is only projected to change slightly. It is reported in the IPCC Fifth Assessment Report (AR5) that it is very likely that global near-surface and tropospheric air-specific humidity have increased since the 1970s. However, during recent years the near-surface moistening trend over land has abated (medium confidence), and fairly widespread decreases in relative humidity near the surface have been observed over the land in recent years.

Importantly, while actual potential evaporation over water is projected to increase, there are likely to be significant variations over land, driven by changes in precipitation and atmospheric evaporative demand. This will result in changes to the regional water balance, including groundwater recharge; catchment run-off; soil moisture; water held in reservoirs; and in cold regions, the snowpack and glaciers; and the salinization of coastal aquifers in combination with sea level rise (see Chapter 5).

Non-climate drivers

Alongside climate change drivers that will influence future freshwater resources, there are non-climatic drivers of change (United Nations, 2003; IPCC, 2007a). These include influences in land-use changes, such as deforestation, and increasing water demand linked to urbanization and irrigation, construction and management of reservoirs, pollution and waste water treatment. Underlying these drivers are population changes (in both absolute numbers and their regional distribution), affluence, food consumption, economic policy (including water pricing), technology, lifestyle factors and also the views of local populations on the use of freshwater, catchments and freshwater ecosystems (Kundzewicz et al., 2007).

Consequently, the potential direct impacts of climate change on water resources, outlined in Appendix 6-2, must be carefully considered alongside potential socioeconomic and biophysical non-climatic drivers, using the methods and approaches outlined in Chapter 3.

Appendix 6-2: Potential impacts

Soil moisture

Any future changes in soil moisture will have significant implications for run-off and stream flow (see section 6.3.4), as well as in-situ agricultural productivity (see Chapter 7).

Unfortunately, the current understanding of the interactions of future temperature, rainfall, evaporation and vegetation changes results in modelling challenges to predict changes in soil moisture. Nevertheless, the global patterns of annual mean soil moisture content commonly show:

- Decreases in the sub-tropics and the Mediterranean region;
- Increases in East Africa, central Asia and some other regions with increased precipitation;
- Decreases at high latitudes, where snow cover diminishes.

Changes in run-off and stream flow

In the chapter on freshwater resources and their management in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) a suite of global climate models (GCMs) was used to simulate future climate under a range of IPCC emissions scenarios (Kundzewicz et al., 2007). These studies linked climate simulations to a large-scale hydrological model to examine changes in annual average surface run-off. These studies found that all simulations yield a global average increase in precipitation, but likewise exhibit substantial areas where there are large decreases in run-off. Thus, the global average of increased precipitation clearly does not readily translate into regional increases in surface and groundwater availability. Rather, there are significant regional variations in run-off that require careful analysis.

Hydrological impacts on coastal zones

AR4 and the Fifth Assessment Report (AR5) (Nicholls et al., 2007; IPCC, 2014) and Bates et al. (2008) identify several key impacts of both sea level rise and altered hydrologic regimes on water resources in the coastal zone. These include but are not limited to:

- Increased inundation and coastal flooding causing salinization of groundwater and estuaries, resulting in a decrease of freshwater availability for humans and ecosystems in the coastal zone;
- Changes in the timing and volume of freshwater run-off affecting salinity, sediment and nutrient availability, and moisture regimes in coastal ecosystems;
- Changes in water quality may come as a result of the impact of sea level rise on storm water drainage operations and sewage disposal in coastal areas and increase the potential for intrusion of saline water into fresh groundwater;
- Increased inundation of coastal wetlands resulting in species displacement;
- Changes to the hydrological regime potentially causing erosion along the coast due to altered sediment budget;

- Changes to the zonation of plant and animal species as well as the availability of freshwater for human use as a result of salinity advancing upstream due to decreased stream flow.

Water quality changes

AR4 found that, in lakes and reservoirs, climate change effects on water quality are mainly due to water temperature variations, which result directly from climate change or indirectly through an increase in thermal pollution as a result of higher demands for cooling water in the energy sector (Kundzewicz et al., 2007). Increased rainfall intensities in mountain areas are likely to increase soil erosion and increased stream flow would increase river bank erosion. The combined effect would be to increase sediment and nutrient loading in rivers and reservoirs. Higher water temperatures and changes in extreme events resulting in floods and droughts are projected to affect water quality and exacerbate many forms of water pollution from sediments, nutrients, dissolved organic carbon, pathogens, pesticides and salt, as well as thermal pollution (Bates et al., 2008).

Further modifications of water quality may be attributed directly to sea level rise, in particular through the direct inundation of low-lying coastal areas impacting freshwater systems and on key water resource infrastructure such as storm water drainage operations, sanitation facilities and reservoirs containing freshwater (Bates et al., 2008).

Changes in groundwater

Generally there are two types of groundwater resources: groundwater from shallow unconfined aquifers; and groundwater from deep confined aquifers. Groundwater within unconfined aquifers is directly tied to near-surface hydrologic processes, including recharge from precipitation and through base-flow to river systems; it is thus intricately tied to the overall hydrologic cycle and could be directly affected by climatic change.

Changes in groundwater will be attributed to changes in inflows (mainly groundwater recharge from rainfall, soil moisture below plant root zones and river–groundwater interaction) and groundwater withdrawal associated with changes in water demand and level of dependency on groundwater resources.

The demand for groundwater is likely to increase in the future, the main reason being increased water use globally. Another reason may be the need to offset declining surface water availability due to increasing precipitation variability in general and reduced summer low flows in snow-dominated basins (Kundzewicz et al., 2007). In many communities, groundwater is the main source of water for irrigation, municipal and industrial demands. In many places, the over-extraction of unconfined aquifers results in a reduction in the level of the water table, because the abstraction rate is greater than the recharge rate. In fact, unconfined aquifers are often thought of as being part of the same resource as surface water because they are hydraulically connected. Thus, climatic changes could directly affect these recharge rates and the sustainability of renewable groundwater. Groundwater supplies within confined aquifers are usually derived from deep earth sediments deposited long ago and so have little climatic linkage. However, these groundwater resources may decline as an indirect result of increased abstraction to account for declining surface water resources.

Climate change is also likely to have a strong impact on saltwater intrusion into aquifers as well as on the salinization of groundwater due to increased evapotranspiration. Sea level rise leads to intrusion of saline water into fresh groundwater in coastal aquifers and thus adversely affects potable groundwater resources (Kundzewicz et al., 2007).

Changes in water demand, supply and sanitation

Climate change could cause increasing problems in providing water services, particularly in developing countries (Kundzewicz et al., 2007). There are several reasons for this, some of which are not necessarily tied to climate change. Various factors already pose a significant challenge to providing satisfactory water services; these include but are not limited to:

- An existing lack of adequate potable water;
- The high cost of water distribution to widely scattered settlements;
- An increased and more spatially distributed water demand as a result of population growth in concentrated areas;
- An increase in urbanization and the associated increase in water use per capita and water pollution;
- More intense public water use;
- Water governance – allocations to industry, agriculture, public and environmental flows.

In light of the above factors, it can be seen that significant challenges are already present within the water services sector. In this context, climate change represents an additional burden for water utilities, or any other party involved in the provision of water services. Some possible observed effects of climate change and its potential impacts on water services are summarized in Table 6-5, below.

Table 6-5
Observed effects of climate change and its observed/possible impacts on water services

Observed effect	Observed/possible impacts
Increase in atmospheric temperature	• Reduction in water availability in basins fed by glaciers that are shrinking, as observed in some cities along the Andes in South America (Ames, 1998; Kaser and Osmaston, 2002) • Possible increase in evaporative losses from soils, drying of soils, reduced run-off and recharge
Increase in surface water temperature	• Reductions in dissolved oxygen content, mixing patterns and self-purification capacity • Increase in algal blooms
Sea level rise	• Salinization of coastal aquifers
Shift in precipitation patterns	• Changes in water availability due to changes in precipitation and other related phenomena (e.g., groundwater recharge, evapotranspiration)
Increase in inter-annual precipitation variability	• Increases the difficulty of flood control and reservoir utilization during the flooding season
Increased evapotranspiration	• Water availability reduction • Salinization of water resources • Lower groundwater levels
More frequent and intense extreme events	• Floods affect water quality and water infrastructure integrity, and increase fluvial erosion, which introduces different kinds of pollutants to water resources • Droughts affect water availability and water quality

Source: Kundzewicz et al., 2007.

Appendix 6-3: Adaptation

This appendix briefly summarizes approaches to water resources adaptation.

Adaptation to climate change consists of strategies that explicitly take climate change and variability into account and/or those that improve resilience to climate change. Adaptations can focus on reducing exposure and sensitivity or on increasing adaptive capacity or both (see Table 6-6). Examples of strategies that improve resilience include (Wilk and Wittgren, 2009):

- Innovative water harvesting systems to supplement household water supply and irrigation practices;
- Restoring defunct or poorly maintained irrigation facilities to improve water efficiency and equity of access;
- Maintaining and establishing wetlands to trap nutrients and provide food and fodder for people and livestock.

Table 6-6
Adaptations to reduce exposure and sensitivity

Option	**Description**
Policies to avoid exposure	Land-use zoning, use restrictions, relocation policies
Sector-level best practices	Selection of climate-resilient crop and tree varieties, water harvesting, use of natural floodplains for water storage, energy efficiency in buildings, water management and lighting
Climate proofing of infrastructure	Increasing resilience to climate impacts through building designs, selection of construction materials, elevated structures
Adaptations to increase adaptive capacity	
Promote economic development and improved and diversified livelihoods	Higher incomes and more diversified livelihoods enable individuals and households to cope with climate change and particularly floods, droughts and extreme events
Strengthen disaster risk management capabilities	Helps civil society and communities respond to droughts, floods and extreme events with fewer fatalities and injuries and recover more quickly
Improve management of public services	Better management of water supply and demand may reduce impact of droughts, complement disaster risk management
Implement early warning systems	Monitoring and decision support systems (DSS) related to floods, drought, health outbreaks and crop/forest diseases and pests
Build multiple support systems	Includes systems such as water supplies, emergency energy systems, transportation and communications, plus food banks
Maintain healthy ecosystems	Ecosystems provide a variety of services such as water regulation and sediment control that can help reduce the impacts of droughts, floods and extreme events; maintain biodiversity; and support natural resource-based livelihoods

Source: USAID, 2010.

Adaptation options that increase the resilience of people and ecosystems by improving access to water and ecosystem services include those that can simultaneously reduce vulnerability towards a variety of stressors, including present climate variability and future climate change, globalization, urbanization, environment degradation, disease outbreaks and market uncertainties.

A wide range of adaptation options are available for diverse biophysical, socioeconomic and institutional contexts. The following examples are suggested by Wilk and Wittgren (2009):

1. Adaptation by increasing water supply and ecosystem services:
    - Expansion of rainwater harvesting to improve rain-fed cultivation and groundwater recharge;
    - Adoption of water transfer schemes;
    - Restoration of aquatic habitats and ecosystem services;
    - Increased storage capacity by building reservoirs;
2. Adaptation by decreasing water demand and increasing water-use efficiency:
    - Removal of invasive non-native vegetation from riparian areas;
    - Improvement of water-use efficiency by water recycling;
    - Spread of drought-resistant crops;
    - Improved management of irrigated agriculture (e.g., changing the cropping calendar, crop mix, irrigation method and repair and maintenance of irrigation infrastructure);
    - Expanded use of economic incentives to encourage water conservation;
    - Improvement of urban water and sanitation infrastructure;
3. Adaptation by improving flood protection:
    - Construction of flood protection infrastructure;
    - Enlargement of riparian areas;
    - Increased upstream storage;
    - Restoration and maintenance of wetlands;
    - Improved flood forecasting.

Adaptive responses by systems and sectors

Water managers have long had to cope with the challenges posed by climate and hydrologic variability, both intra-annually and inter-annually. Their adaptation strategies have included responding to both seasonal variability and extended wet and drought periods by using integrated reservoir and irrigation systems that allow for the capture of water during the wet season for use during dry seasons and extended drought periods. These ***autonomous adaptation*** actions – which are defined as responses that will be implemented by individual water managers, farmers and other water users – will depend on perceived or real climate change in the coming decades, and without intervention and/or coordination by regional and national governments and international agreements (Bates et al., 2008). In addition, ***planned adaptation*** (using the definition from the Intergovernmental Panel on Climate Change (IPCC), which includes changes in policies, institutions and dedicated infrastructure) will be needed to facilitate and maximize long-term benefits of adaptation responses to climate change.

In most parts of the world, particularly in Africa, women and children are responsible for collecting water for cooking, cleaning, health and hygiene. Increasingly limited water supplies, poor service delivery and pollution are jeopardizing women's survival and that of their families (IUCN, UNDP and GGCA, 2009). Both women and men can be agents of change and therefore the starting point is an analysis of the differentiated relationship that women and men have with environmental resources such as water.

A clear understanding of the relationships between gender and sustainable development requires an analysis of patterns of use and knowledge and skills related to managing, using and conserving natural resources. Applying a gender approach will ensure a complete view of the relations people have built with their ecosystems (IUCN, UNDP and GGCA, 2009).

The IPCC Technical Paper, *Climate Change and Water* (Bates et al., 2008), provides a thorough description of potential *autonomous* and *planned* adaptive responses, embedded within the context of vulnerability and sustainable development on water resources in systems and sectors. Each system or sector is described in turn in the following sections, based on the IPCC Technical Paper, *Climate Change and Water* (Bates et al., 2008), and IPCC AR4.

Water Resource Adaptation in Agriculture and Food Security, Land Use and Forestry

A key focus for *autonomous* adaptations with respect to water resources and agriculture, food security, land use and forestry is enhancement of the risk management and production-enhancement activities already available to farmers and communities – or the creation of new support services. For example, with respect to water and crop agriculture, these include:

- Adoption of varieties/species with increased resistance to heat shock and drought
- Modification of irrigation techniques, including amount, timing or technology
- Adoption of water-efficient technologies to 'harvest' water, conserve soil moisture (e.g., crop residue retention) and reduce siltation and saltwater intrusion
- Improved water management to prevent waterlogging, erosion and leaching
- Modification of crop calendars (i.e., timing or location of cropping activities)
- Implementation of seasonal climate forecasting

Options for planned adaptation include the implementation of actions to:

- Improve governance, including addressing climate change in development programs
- Increase investment in irrigation infrastructure and efficient water-use technologies
- Ensure appropriate transport and storage infrastructure
- Revision of land tenure arrangements (including attention to well-defined property rights)
- Establishment of accessible, efficiently functioning markets for products and inputs (including water-pricing schemes)
- Financial services (including insurance)

Further information on autonomous and planned adaptive responses for agriculture and food security and forestry are provided in Chapter 7, while further information on adaptation of coastal land use is shown in Chapter 5.

Water Resource Adaptation in Human health

> *Due to the very large number of people that may be affected, malnutrition and water scarcity may be the most important health consequences of climate change* (Bates et al., p. 67).

Adaptation activities to mitigate the impacts of future climate change–driven changes in the water resources sector include vulnerability-reduction activities to enhance access to potable water and improved sanitation to reduce malnutrition, infant mortality and diseases related to contaminated or insufficient water.

In addition, as outlined in Chapter 8, the use of health impact assessments often reveals opportunities to embed the health effects of any adaptation strategy into the water sector, such as those in water supply and sanitation, as outlined below.

Water Supply and Sanitation Adaptation

The critical issue for governments and water utilities located in regions at risk from significant changes in future freshwater is to develop effective, long-term adaptation plans. This is especially important given that water supply and sanitation systems are engineered systems with long life expectancies, for which the traditional water planning paradigm has been to assume that observed historical climatic conditions will be representative of future conditions.

Adaptive options include:

- The construction of new storage reservoirs
- Using alternative water sources, such as groundwater or desalinization
- Reducing the need for new water supplies include rainwater harvesting as well as controlled reuse and minimizing water losses (leaks) in urban networks and in irrigation systems

- Development of water safety plans (WSPs) to perform a comprehensive assessment and management of risks from the catchment to consumer to address lower water quality caused by flow variations
- Design and operation of water and wastewater treatment plants should be reviewed periodically, particularly in vulnerable areas, to ensure or increase their reliability and their ability to cope with uncertain flow variations
- Use of decentralized systems, the construction of separate sewers, the treatment of combined sewer overflows (i.e., the mixture of wastewater and run-off in cities) and injecting rainwater into the subsoil

The above adaptive options can also be completed by enhanced integrated water management practices that seek to integrate change adaptation into policy and practice, as outlined in Chapter 9.

Water Resource Adaptation in Settlements and Infrastructure

Importantly, the IPCC Technical Paper, *Climate Change and Water* (Bates et al., 2008), stressed, with very high confidence, that improved incorporation of current climate variability into water-related management would enhance adaptation responses. Enhanced management arrangements to address the impacts of floods or drought, or the quantity, quality or seasonal timing of water availability, is one example. However, it is recognized that many of these adaptive responses will likely be expensive and, as a result, careful consideration of the costs will be required. In this respect, it is useful to consider water resource adaptation in the following contexts:

- Settlements in high-risk locations, such as coastal and riverine areas, due to flood and storm damages and water-quality degradation as a result of saline intrusion
- Settlements whose economies are closely linked to a climate-sensitive, water-dependent activity, such as irrigated agriculture, water-related tourism and snow skiing
- Infrastructure, including buildings, transportation networks, coastal facilities, water supply and wastewater treatment infrastructure and energy facilities, exposed to direct water-related climate change damage (e.g., flooding, subsidence due to soil drying) as well as impacts on the performance, cost and adequacy of facilities that were not designed for climate change