IPCC WGII Fourth Assessment Report –Draft for Government and Expert Review

Chapter 3 - Freshwater Resources and their Management

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Contents

Executive Summary

Since water impacts tend to be regional, relevant material can be also found in regional chapters (9-16). Information about trends in water-related observation data is covered in chapter 1. This chapter aims to give a general overview on water-climate change issues.

The key emerging findings regarding freshwater and their management in relation to a global perspective of current vulnerabilities, future impacts and vulnerabilities and adaptation to climate change are summarized below. Each statement has an associated level of confidence. The statements are organized from high confidence to low confidence.

- The most certain impact of climate change on freshwater and its management is due to the increases in temperature, precipitation variability and sea level rise [high confidence, 3.3.1, 3.4.1, 3.4.3]. More than one sixth of the world population live in snowmelt-fed river basins and will be affected by reduction and seasonal shift in streamflow caused by decreased snow water storage. Sea level rise will extend areas of salinization of groundwater. Thus, freshwater availability in coastal areas will decrease.

- Climate-driven changes in volume and timing of river flow have already been observed and had effects on water management [high confidence, 3.2]. In many pristine rivers in North America, climate-related increase of winter runoff has been detected. In some regions, changes in volume and timing of snowmelt have led to water supply decrease. In Australia, a strong decrease in precipitation during the last decades has caused large investments in water management.

- There has been evidence of global increase in the number and extent of very dry areas [high confidence, 3.1.1]. Intensification of the hydrological cycle is projected to increase the risk of floods and hydrological droughts in many areas [high confidence, 3.4.4].

- Quantitative projections of changes in river flows and water levels at the basin scale, especially beyond 2020, remain uncertain [high confidence, 3.3.1, 3.4.1]. Since TAR, uncertainties have been evaluated and their interpretation has improved. However, simulation of precipitation by climate models still remains largely uncertain. Uncertainty about water availability (river flow and groundwater) has implications for adaptation procedures which need to be developed based on imperfect projections of changes, for example, in river discharge or groundwater. Furthermore, some water-related consequences of climate policies and emission pathways cannot be assessed with high reliability.

- Warming and extreme events exacerbate different types of water pollution (e.g. nitrates, dissolved organic carbon, pathogens, thermal pollution) with impact on human health and the environment. It can be expected that impact of climate change on other pollutants will become evident in the future [high confidence, 3.4.5].

- Climate change is one of multiple pressures on water resources [high confidence, 3.1.1]. In many areas and in particular in water-scarce areas, anthropogenic pressures such as population and economic growth, land use and urbanization, in addition to climate change, are factors behind adverse changes in freshwater resources. However, in some areas (e.g. Mediterranean basin, including Northern Africa, Western Australia) water resources are particularly vulnerable to climate change (see Figure 3.3)

- Water management should incorporate impacts of climate change since the stationarity assumption—that the past is representative of the future—is not longer valid [high confidence, 3.6].Water management in some countries has adopted allowances for climate change and risk management approach in order to account for the uncertainties (e.g., Caribbean, Canada, Australia, Netherlands, UK, California).

- Globally, water demand will grow due to climate change [medium confidence, 3.5] and groundwater recharge in some already water-stressed regions will decrease very strongly [medium confidence, 3.4.3].

- Reduction in transpiration from plants due to direct physiological effects of rising CO_2 may lead to a greater increases or smaller decreases in runoff compared to those expected from climate change alone (medium confidence, section 3.4.1). There is evidence from models that past increases in continental runoff are attributable to this effect (low confidence, section 3.4.1).

3.1 Introduction

Water is indispensable for all forms of life. It is needed in large volumes virtually in any human activity. Access to safe freshwater is now considered as a universal human right and extending access to safe drinking water is one of the Millennium Development Targets.

The climatic and freshwater systems are interconnected in complex ways. Any change in one of these systems induces a change in the other. Climate change exerts considerable impact on the freshwater resources and their management. This applies to water in all forms (liquid, solid, gaseous), and to both quantity and quality aspects. As an example, the variation in rainfall and river flow regime observed during the 20th century in the Nile basin exerted a strong influence on the society, affecting food security and forcing adaptation measures across various scales (Conway 2005).

Human activities such as changes in land cover, modification and compression of soil layers, urbanization and agriculture, have large effects on water cycles. Anthropogenic impacts on surface and subsurface water cycles may have indirect effects on atmospheric circulation and regional climate. For example, large scale deforestation or draining of large wetlands may cause change in moisture recycling and a decrease of precipitation in particular months, when local boundary conditions dominate over large-scale circulation (Kanae *et al.* 2001).

Figure 3.1 schematically illustrates the impacts of population growth, economic activities, and consumptive life style on the hydrological cycle, water use, and the resulting change in water stress (Oki 2005). Water withdrawals increase directly with the growth of population and water usage per capita, and indirectly through increased irrigated food production. Increase in demand for food and industrialization drives changes in land use and increases the emission of the greenhouse gases contributing to climate change. Any change on water supply side (hydrological cycle) and on the demand side (water withdrawals) necessitates adaptation in the management of water resources.

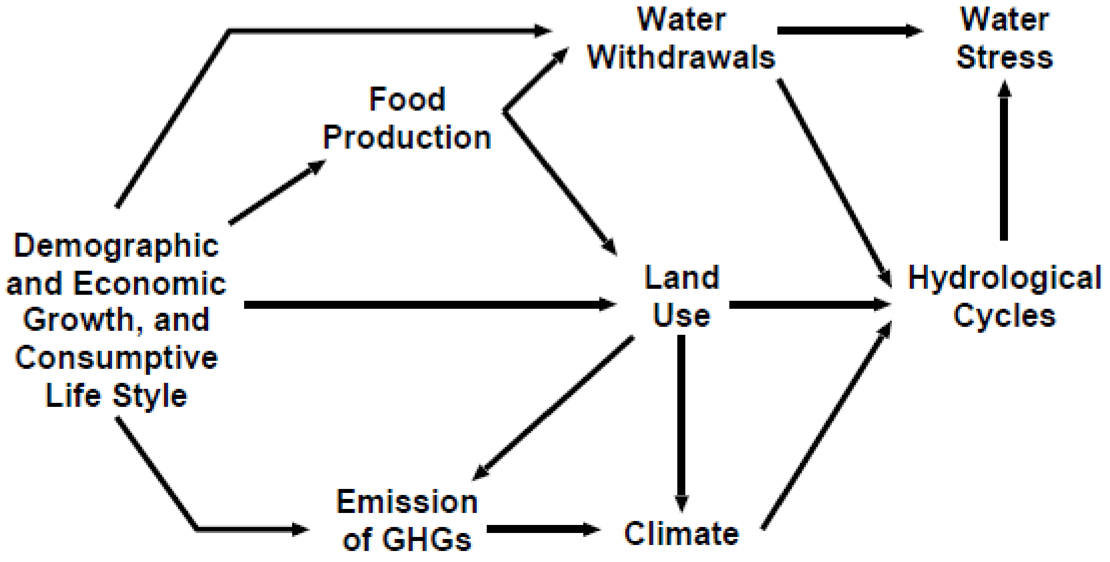


***Figure 3.1:** Diagram illustrating major pathways of changes. Demographic and economic growth, and increasingly consumptive life style, drive the changes in hydrological cycles and freshwater resources through changes in land use, water withdrawals, and climate related to food production and the emission of the greenhouse gases (GHGs). (Source: Oki 2005).*

In the TAR, the state of knowledge of climate change impacts on hydrology and water resources was presented in the light of literature up to 2000 inclusive (Arnell and Chunzhen Liu 2001). Basic understanding of climate change and its implications for the hydrological cycle, water resources and their management were presented with regional and sectoral interpretation. These TAR findings are summarized as follows:

- There are apparent trends in streamflow volume, both increases and decreases, in many regions.
- The effect of climate change on streamflow and groundwater recharge varies regionally and between scenarios, largely following projected changes in precipitation.
- Peak streamflow is likely to move from spring to winter in many areas due to early snowmelt.
- Glacier retreat is likely to continue, and many small glaciers may disappear.
- Generally, water quality is likely to be degraded by higher water temperature, but this may be offset regionally by increased flows, leading to increased dilution.
- Flood magnitude and frequency are likely to increase in most regions, and low flows are likely to decrease in many regions.
- Demand for water is increasing as a result of population growth and economic development, but is falling in some countries, due to higher water use efficiency and water pricing.
- The impact of climate change on water resources also depend on system characteristics, changing pressures on the system, how the management of the system evolves, and what adaptations to climate change are implemented.
- Climate change challenges existing water resources management practices by adding uncertainty.
- Adaptive capacity is distributed very unevenly across the world.

This chapter gives an overview of the future impacts of climate change on freshwater resources, including socio-economic aspects, adaptation issues, implications for sustainable development, key vulnerabilities, and uncertainty problems.

3.2 Current sensitivity/vulnerability

3.2.1 Climatic variations and water resources management

Climate-induced changes in the physical processes constituting the water cycle, in quantity (amount, frequency and intensity), quality, and phase will require adaptation by water resources management. Since the rate and magnitude of the projected future changes is unprecedented, agriculture and in particular forestry might not be able to adapt (Salinger 2005, adaptation). As summarized in Chapter 1, various trends have been detected in observed records of physical processes partaking in the water cycle. However, other non-climatic drivers (as illustrated in Figure 3.1) have also been exerting considerable pressure on water resources management.

It is increasingly recognized that “freshwater availability and use” should refer both to humans and to other living organisms, in particular to aquatic ecosystems. Human water use is dominated by irrigation, which accounts for almost 70% of the global water withdrawals amounting approximately to 3500 km^3/year (Shiklomanov 2003). The remaining withdrawal volumes are shared almost equally by the sectors: thermal power generation, manufacturing and households (including public and commercial water demands) (Vassolo 2005). Irrigation accounts for more than 90% of global consumptive water use (Shiklomanov 2003), defined as the water volume that is lost during use and is thus not available for reuse downstream. Human water use during the last decades was overwhelmingly driven by non-climatic factors. In most countries of the world, except some industrialized countries, per-capita water use has increased over the last decades due to economic growth in general and improved water supply in particular.

Currently, humans and natural ecosystems in many river basins suffer from a lack of water. In global-scale assessments, basins with "severe water stress" are defined either by a per-capita water availability below 1000 m^3/yr (based on long-term average runoff) or a ratio of withdrawals to long-term average annual runoff above 0.4. These basins are located in the Mediterranean region, the Near East, South Asia, Northern China, Australia, the USA and Mexico. The estimates for the population living in such severely stressed basins range from 1.4 billion to 2.1 billion (Oki *et al.* 2003; Alcamo *et al.* 2003; Vörösmarty *et al.* 2000; Arnell 2004). Due to the strong population growth in most of the severely stressed basins, water stress is very likely to have increased independently of the impact of climate change.

Groundwater and climate are linked in many ways. Groundwater systems generally respond more slowly to variability in climate conditions than do surface water systems. The areas with relatively higher hydrological variability are not necessarily more sensitive to climatic changes. The location of permeable layers (prone to groundwater rise) in relation to high storages (lower stress) and higher gradients (higher stress) influences the sensitivity of a site with respect to climate changes (Schmidt and Dikau 2004).

Data compiled by Berz (2001) shows that the number of great flood disasters (those requiring international or inter-regional assistance) in the nine years 1990-1998 was higher than in earlier three-and-half decades, 1950-1985, together. Part of the observed upward trend in flood damage is linked to socio-economic factors, such as increase in population and in wealth gathered in vulnerable areas, and land-use change. Floods have been the most reported natural disaster events in Africa, Asia and Europe, and have affected more people across the globe (140 million per year on average) than all other natural disasters (WDR 2003, 2004). In Bangladesh three extreme floods in the last two decades inundated about 70 % of the country (Mirza 2003). In India, on average, floods have affected about 33 million persons a year between 1953-2000 (Mohapatra and Singh 2003). It is not rare that material flood damage in one season and one country exceed 10 billion USD (e.g., USA, 1993; Italy, 1994; China, 1996 and 1998; Germany, 2002).

In lakes and reservoirs, climate change effects are mainly due to water temperature changes, which result directly from climate change or indirectly through an increase of thermal pollution as result of higher demand for cooling water in the energy sector. This affects oxygen regimes, redox potentials, lake stratification, mixing rates and biota development as they all depend on temperature. Climate change also affects the water temperature and the self-purification capacity of rivers, reducing the amount of oxygen than can be dissolved and used for biodegradation. In the Fraser River in British Columbia (Canada), longer sections of the river have reached a temperature over 20°C, which is considered as a threshold for degrading salmon habitat (Morrison *et al.* 2002). It was found that due to precipitation change, nitrogen loads from rivers flowing to the Chesapeake and Delaware bays increased by up to 50% (Chang *et al.* 2001). Aquifer salinization is a problem caused not only by sea level rise. Warmer and drier periods of reduced groundwater recharge provoke saline water to intrude into freshwater areas in Manitoba, Canada (Chen *et al.* 2004).

Several diseases can be transmitted via water, either by drinking it or by consuming crops polluted by irrigated water. The presence of pathogens in water supplies has been linked with extreme rainfall events (Curriero *et al.* 2001; Cox *et al.* 2003; Hunter 2003; Yarza and Chase 1999; and Faver *et al.* 2002). In aquifers, a possible relation between presence of viruses and extreme events has been mentioned (Hunter 2003). On the other hand, water quality effects of dry periods have not been adequately studied (Takahashi *et al. 200*1), although it is clear that lower water availability (dilution) leads to higher pollutant concentration.

Coastal regions at present undergo the fastest population rise, already accounting one fourth of the world population), but are also water-scarce, with less than 10 % of the renewable water supply (Millennium Ecosystem Assessment 2004). Saline intrusion due to excessive water withdrawals from aquifers is exacerbated by the effect of sea level rise, leading to even higher salinization and reduction of freshwater availability (Klein and Nicholls 1999; Sherif and Singh 1999; Peirson *et al.* 2001; Essink 2001; Beach 2002; Beuhler 2003). Salinization also affects rivers; e.g. in the Mary River in Australia saline intrusion advances by more than 0.5 km/yr (Mulrennan and Woodroffe 1998), and a similar effect has been observed in the Mississippi River delta (Burkett *et al.* 2002).

Water quality problems, especially the microbial aspects, and their effects are different in kind and magnitude in developed and developing countries, mainly from the microbial point of view (Jimenez 2003 and Lipp *et al.* 2001). In developed countries, waterborne diseases linked with floods are contained by well maintained water and sanitation services (McMichael *et al.* 2003) but this does not apply in developing countries (Wisner and Adams 2002). Regretfully, except for cholera and salmonella, studies relating climate change with the micro-organisms content in water and wastewater do not refer to pathogens of interest in developing countries (Scott *et al.* 2004; Cox *et al.* 2003; Fayer *et al. 2003*; Rose *et al.* 2001; Yamamoto *et al.* 2000; Yarze and Chase 1999). In developing countries, intermittent water supply during drought, lead to a drop of water quality water in networks. It is estimated that one third of urban water supplies in Africa, Latin America and the Caribbean, and more than half in Asia, are operating intermittently (WHO/UNICEF 2000).

The water-holding capacity of the warmer atmosphere increases, and the increase in evaporation is likely to favour stronger rainfall and drought occurrence (Trenberth 1998), thus enhancing the hydrological cycle (Huntington 2006). Rainfall amounts and intensities are the most direct and important factors controlling climate change impact on erosion (Nearing *et al.* 2005). Each 1% change in average annual precipitation induce 2.0% change in runoff and a 1.7% change in erosion (Pruski & Nearing 2002a).

Gedney *et al.* (2006) attributed an observed 3% rise in global river flow over the 20th century to CO_2 forcing by plants enhancing river flows by 5% with a 2% offset by climate change. This implies that the annual global land-atmosphere moisture flux has decreased by approximately 60,000 tonnes of water per second due to physiological controls.

All levels of government, as well as the private sector and individual stakeholders, are regularly engaged in the water management. Management involves being responsible and accountable for the regulation, control, allocation, distribution and efficient use of existing supplies of water to offstream uses such as for example, irrigation and power cooling. Water management also involves the development of new supplies, control of floods and the provision of water for instream uses, such as navigation and environmental flows (Appleton *et al.* 2003, Smakhtin *et al.* 2006).

Many of the commonly recommended adaptation options to address climate change in the water sector, including water conservation and preparedness for extreme events, are based on strategies for dealing with current variability. Structural adaptations, such as dams, weirs and drainage canals, tend to increase the flexibility of management operations, although these adaptation options generate social and environmental costs. Upgrading existing infrastructure to better deal with future climates may often be preferable to building new structure. Design decisions should reflect extreme events and system thresholds, rather than focussing on changes in the mean conditions. It is also important to see water demand management (e.g., reducing consumer demands) as part of the adaptation strategy.

3.2.2 Global perspectives of current vulnerabilities

In some regions on the Globe, freshwater resources are particularly vulnerable to current climatic variations, and prone to cause water-related. A few examples are introduced here.

Inflow to the Aral Sea was reduced due to the irrigation withdrawal, and the sea surface has shrunk to half of its former size, the water levels have fallen by more than 13 metres, and the mineral content has increased fourfold, effectively killing off the fish population (Clarke and King 2004). Similarly, the Yellow River reduced its flow volume due to excessive withdrawals for irrigation (Yang *et al.* 2004). In a year with low precipitation, 1997, river ran dry for more than 200 days at the distance of 700 km. Fortunately, no river dry-up has been observed since 2000, due to the counter-measures, which were adopted and implemented (Xu 2005). In the Murray-Darling River, reduced flows do not allow to meet water demands of irrigation, municipal water supply, and environmental flows necessary for freshwater wetlands. Due to high withdrawals, flow in the Colorado River has also been reduced and become highly saline, consequently downstream Mexico has been deprived of an important resource. Since the USA has treaty obligations to provide Mexico with at least l.8 cubic kilometres of water a year, it has been forced to build a desalination plant to ensure that Mexico gets freshwater (Clarke and King 2004).

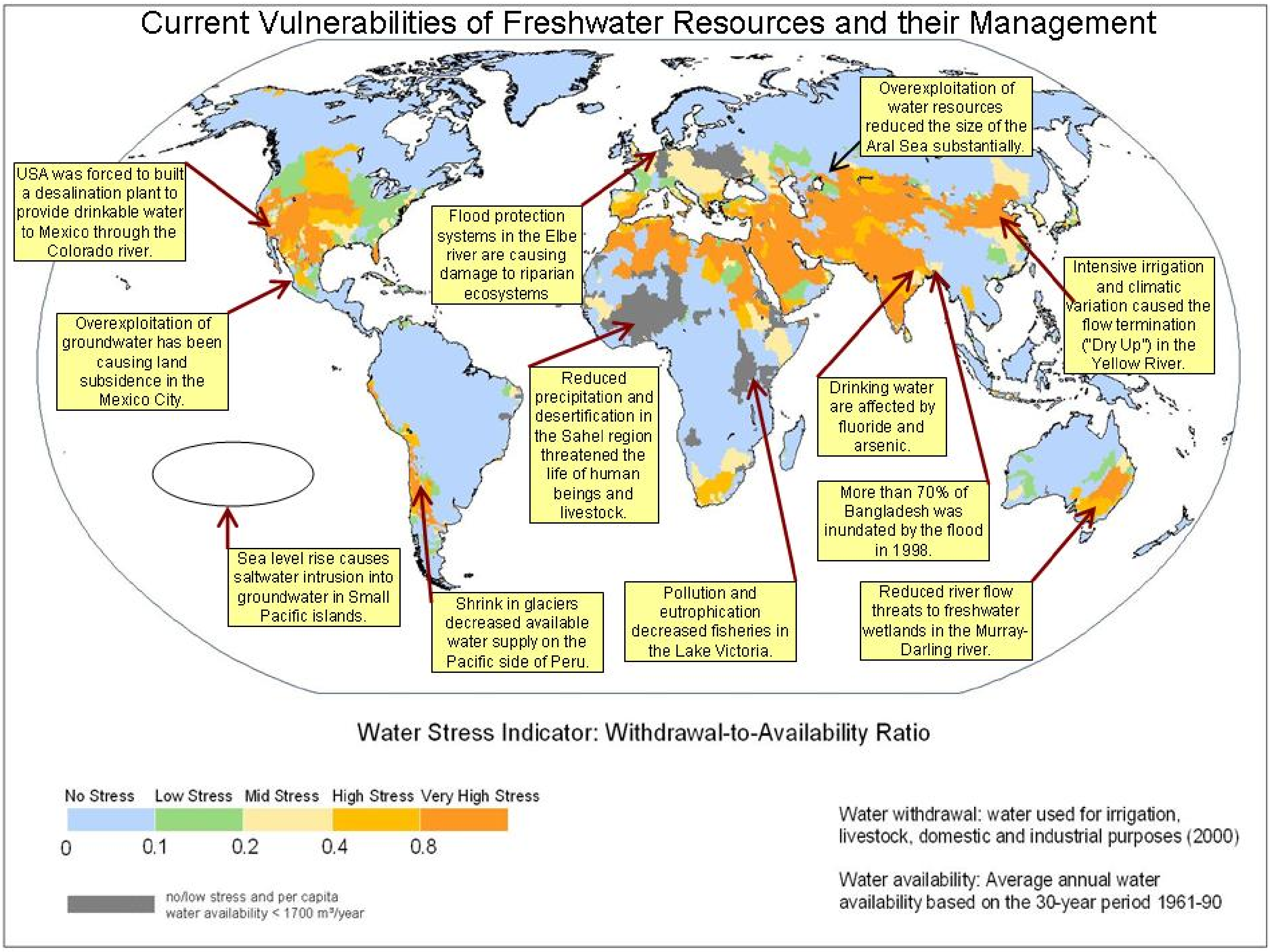
In places such as Mexico City, which are located in water-stressed areas and struggling to meet the water needs of their growing populations, groundwater overexploitation has caused serious land subsidence (Clarke and King 2004). In the case of Lake Victoria, pollution and eutrophication of the lake water has become serious due to the inflow of untreated wastewater from increasing population on the lake, leading to decrease in fisheries, serious damage on the local industry and malnutrition.

A relatively recent discovery is the high level of arsenic found in groundwater supplies in many different parts of the world (Clarke and King 2004). The situation has become extremely serious over large areas in Bangladesh, ironically as a result of a programme of drilling deeper boreholes to obtain better quality water. Fluorosis, caused by the build-up of fluoride, is another major water-related public health problem in many parts of Asia and North Africa.

In Bangladesh, flooding is a commonplace occurrence, but in 1998, about 70% of the country area was inundated, more than 1000 people lost their lives, and more than 30 million people lost their shelter (Mirza 2003, Clarke and King 2004). In such areas like the Elbe river basin, increasing flood risk drives strengthening of flood protection systems by structural means, with detrimental effects to riparian ecosystems and freshwater wetlands (Wechsung *et al.* 2005).

Climatic changes have already caused serious problems in the freshwater resources and their management. Since 1970s, precipitation and available water resources have been reduced in the Sahel region, and it caused serious, and long-lasting, drought and famine in the region (L'Hote *et al.* 2002). The sea level rise has caused saline intrusion into freshwater aquifer and increased the risk of coastal surges, for example in the Small Pacific islands as discussed in Chapters 6 and 16. Shrinking of Andean glaciers results in the decrease in water supply even though 80% of the water resources originate from snow/ice melt on the Pacific side of Peru (Coudrain *et al.* 2005).

These cases are schematically illustrated in Figure 3.2. Water issues mainly due to the water scarcity are well corresponding to the areas with high water stress represented by the withdrawal-to-availability ratio or low per capita water availability.



Current Vulnerabilities of Freshwater Resources and their Management

USA was forced to built a desalination plant to provide drinkable water to Mexico through the Colorado river.

Overexploitation of groundwater has been causing land subsidence in the Mexico City.

Flood protection systems in the Elbe river are causing damage to riparian ecosystems

Reduced precipitation and desertification in the Sahel region threatened the life of human beings and livestock.

Overexploitation of water resources reduced the size of the Aral Sea substantially.

Intensive irrigation and climatic variation caused the flow termination ("Dry Up") in the Yellow River.

Drinking water are affected by fluoride and arsenic.

More than 70% of Bangladesh was inundated by the flood in 1998.

Sea level rise causes saltwater intrusion into groundwater in Small Pacific islands.

Shrink in glaciers decreased available water supply on the Pacific side of Peru.

Pollution and eutrophication decreased fisheries in the Lake Victoria.

Reduced river flow threats to freshwater wetlands in the Murray-Darling river.

Water Stress Indicator: Withdrawal-to-Availability Ratio

Water withdrawal: water used for irrigation, livestock, domestic and industrial purposes (2000)

Water availability: Average annual water availability based on the 30-year period 1961-90

Figure 3.2: *Current vulnerabilities of freshwater resources and their management. (Background water stress indicator map - Döll 2005).*

3.3 Assumptions about future trends

This section describes how the driving forces of freshwater systems are assumed to develop in the future. In Chapter 2 of the AR4 WG2 report, scenarios of the main drivers of climate change and their impacts are presented. In this chapter, the focus is on the dominant drivers of freshwater systems during the 21st century, distinguishing between climatic (principally, precipitation, temperature, and sea level rise) and non-climatic factors. Non-climatic drivers, which are not discussed in Chapter 2, include dam construction, wastewater treatment and irrigation. Assumptions about future non-climatic drivers are necessary to assess vulnerability to climate change impacts but also to compare the relative importance of climate-related changes to changes due to other drivers.

3.3.1 Climatic drivers

Projections for the future

The most dominant climatic drivers for water availability are precipitation, evaporation and snowmelt. In snowmelt-fed basins, future temperature changes are very important, while in coastal areas sea-level rise is a dominating factor. Another important climate variable is the evaporative demand determined by temperature, radiation, humidity and wind speed (cf. Chapter 10 of WG1 report).

Globally, precipitation increases due to climate change (general increases are projected in humid tropics, e.g. the monsoon regions, and at high latitudes), but in some regions (subtropics) precipitation strongly declines (Executive Summary, WG1). While temperatures are expected to increase during all seasons of the year, although with different magnitudes, precipitation may increase in one season and decrease in another. Intensity of rainfall events increases in the tropic and at mid and high latitudes and precipitation extremes increase more than the mean in most areas. In Europe, intensity of rainfall events is projected to increase even in regions where the mean annual precipitation decreases (Christensen & Christensen 2003, Kundzewicz *et al.* 2006). Precipitation patterns are expected to show more intense events, separated by longer dry (or with little precipitation) periods. For mid and high latitude of the Northern Hemisphere, climate models generally predict less precipitation in the summer and more in the winter (Section 10.3.6.1 of WG1).

The most likely global temperature increase until the 2020s is around 1°C, as compared to pre-industrial time for all SRES scenarios. Until the end of the 21st century, the most likely increases are 3-4°C for emissions scenario A2, and around 2°C for B1 (Section 10.5.4.5 of WGI report, Fig. 10.5.17). In the summer, temperature increases are projected to be stronger than in winter except for very northern latitudes (Section 10.5.4.6 of WG1 report, Fig. 10.5.18). Global sea level rise with respect to the year 2000 is expected to reach 5-13 cm by 2050 and 13-38 cm by 2100 (Section 10.6.5 of WG1 report)

Uncertainties

The relative significance of uncertainties in the impact of climate change on water resources depends on the time horizon. In the near-term (e.g. 2020s), climate and hydrological model uncertainties will play important roles. However, over longer time-horizons (2050s onwards), uncertainties due to the choice of emission scenarios will become more significant (Jenkins and Lowe 2003).

Projections based in GCMs are complex and not easy to incorporate into impacts studies due to large uncertainties (Kanlikar *et al.* 2005). The Coupled Model Intercomparison Project (Covey *et al.* 2003) analysed outputs of 18 GCMs. Compared to re-analysed data, most GCM fail to produce consistent precipitation simulations, while temperature simulations are well correlated with observations. These uncertainties, in turn, could induce biases in the simulation of river flows when using directly GCM-outputs representative of current time-horizon (Prudhomme 2006). Moreover, precipitation changes predicted from climate models depend heavily on the simulations of present-day precipitation (Allen & Ingram 2002).

For the same emission scenario, different global climate models produce very different patterns of climate change. The agreement with respect to projected changes of temperature is much higher than with respect to changes in precipitation (Section 10.5.4.3 and Fig. 10.5.15 of WG1 report). Over several regions, models disagree in sign of change of precipitation (Murphy *et al.* 2004, IPCC 2001). Parameter uncertainty of a climate model leads to a much wider range of computed regional changes in precipitation than those derived by scaling a single ensemble member by different climate sensitivities (Murphy *et al. 200*4). To reduce uncertainties, the use of numerous runs from different GCMs with varying model parameters (multi-ensemble runs, e.g. Murphy *et al.* 2004) or thousands of runs from a single GCM as from the *climate.net* experiment (e.g. Stainforth *et al.* 2005) is often recommended. This allows the construction of probability scenarios of future changes (e.g. Murphy *et al.* 2004; Palmer & Räisänen 2002). However, such large ensembles are difficult to use in practice when undertaking an impact study on freshwater resources. Thus, often ensemble means are used instead, despite such scenarios failing to reproduce the range of simulated regional changes, particularly for sea level pressure and precipitation (Murphy *et al.* 2004). An alternative is to consider few outputs from several GCMs.

Future changes of ENSO interannual variability differ between climate models, so that it is not clear yet whether the droughts and heavy rains related to ENSO will intensify with climate change (Executive summary of chapter 10 of WG1 report).

The uncertainties of climate change impact on water resources have been shown to be mainly due to the uncertainty in precipitation inputs and less due to the uncertainties in greenhouse gas emissions (Arnell 2004; Döll *et al. 200*3), in climate sensitivities (Prudhomme *et al. 200*3) or in the hydrological models themselves (Kaspar 2003).Comparison of different sources of uncertainties in flood statistics on two catchments in Britain (Kay et al 2006)led to the conclusion that uncertainty from GCM structure is the largest source of uncertainty, greater than uncertainty due to emission scenarios and to hydrological modelling. Similar conclusions where made (Prudhomme & Davies 2006) on mean monthly flows and low flow statistics in Britain.

Multi-model probabilistic approaches are preferable to using the output of only one climate model, when assessing uncertainty in the climate change impacts on water resources. Since the TAR, many hydrological impact studies have used multi-model climate input (e.g. Arnell 2004 at the global scale, and Jasper *et al. 200*4 at a river basin scale), but studies incorporating probabilistic assessments are rare.

Precipitation-driven changes in hydrological regimes (e.g., river flow) could take longer to detect than temperature driven changes. This reflects variations in the signal to noise (inter-annual variability) ratio of precipitation and temperature and hence different time-scales for detection (Ziegler *et al.* 2005, detection).

Implementation of changing climatic drivers in freshwater impact studies

Most climate change impact studies for freshwater consider only changes in precipitation and temperature, based on changes in the averages of long-term monthly values as provided by climate models, which, at the global scale, are available from the IPCC Data Distribution Centre (http://ipcc-ddc.cru.uea.ac.uk/). In many impacts studies, time series of observed climate values are scaled with the computed change in climate variable to obtain scenarios that are consistent with present-day conditions. This scaling aims to minimize the impacts of the error in climate modelling of the GCMs under the assumption that the biases in climate modelling are of similar magnitude for current and future time horizons. This is particularly important for precipitation projections, where there are substantial differences between the observed values and those computed by climate models. Model outputs could also be biased and the evaluation of changes in runoff being underestimated (e.g. Arnell *et al.* 2003 in Africa, Prudhomme 2006, in Britain). Changes in inter-annual or daily variability of climate variables are generally not taken into account in hydrological impact studies. This leads, among other elements to an underestimation of future floods and droughts as well as irrigation water requirements.

Another problem in the use of GCM outputs (direct, or through changes in mean monthly variables) is the difference in spatial grid scale of GCM (typically several hundred kilometres) and of hydrological processes. Moreover, the resolution of global models precludes their simulation of realistic circulation that leads to extreme events (Christensen & Christensen 2004; Jones *et al.* 2004). To overcome these problems, techniques that downscale GCM outputs to a finer spatial (and temporal) resolution have been developed (TAR, Giorgi *et al.* 2001). They are: dynamical downscaling technique, based on physical/dynamical links between the climate at the large and at smaller scales (e.g. high resolution Regional Climate Models RCMs) and statistical downscaling methods using empirical relationships between large-scale atmospheric variables and observed daily local weather variables. The main assumption is that the statistical relationships identified for current climate will remain valid under changes in future conditions. Downscaling techniques may allow to incorporate daily variability in future changes (e.g. Diaz-Nieto and Wilby 2005) and to apply a probabilistic framework to produce information on future river flows for water resource planning (Wilby and Harris 2005). These approaches help to quantify the relative significance of different sources of uncertainty affecting water resource projections.

3.3.2 Non-climatic drivers

Many non-climatic drivers affect freshwater resources at the global scale (UNESCO 2003). Water resources, both in quantity and quality, are influenced by land-use change, construction and management of reservoirs, groundwater overexploitation and water and wastewater treatment. Water use is driven by changes in population, food consumption, economy (including water pricing), technology, life style and society's views about the value of freshwater ecosystems. It can be expected that the paradigm of Integrated Water Resources Management will be increasingly followed all around the world, so that water as a resource and a habitat will come more into the centre of policy making.

Chapter 2 provides an overview of the future development of non-climatic drivers, including: population, gross domestic product, land cover and sea level, focusing on the IPCC SRES scenarios. In this section, assumptions about key freshwater-specific drivers for the 21st century are discussed.

In developing countries, new reservoirs will be built in the future, even though their number is likely to be small compared to the already existing 45,000 large dams (World Commission on Dams 2000; Scuddler 2005). In developed countries, the number of dams is very likely to remain stable. Furthermore, the issue of dam decommissioning is being discussed in a few developed countries, and some dams have already been removed in France and the USA (Howard 2000). Consideration of environmental flow requirements can lead to modified reservoir operations so that the human use of the water resources might be restricted. Increased future waste water reuse and desalination are means of increasing water supply in semi-arid and arid regions (cf. Ragab 2002; Abufayed 2003). The cost of desalination including the transport of water, will continue to decline, hence, desalination will increasingly be an option for water supply of not only coastal towns (Zhou 2005). However, there are negative impacts of brine disposal and high energy consumption.

Wastewater treatment is an important driver of water quality, and an increase of wastewater treatment in both developed and developing countries can improve water quality in the future. In the EU, for example, more efficient wastewater treatment as required by the Urban Wastewater Directive and the European Water Framework Directive will lead to a reduction of point-source nutrient input to the rivers. However, organic micro-pollutants (e.g. endocrine substances) are expected to occur in increasing concentrations in surface waters and groundwater. This is because the production and consumption of chemicals are likely to increase in the future in both developed and developing countries (Daughton 2004) and several of these pollutants are not removed by current wastewater treatment technology. In developing countries, increase in point emissions of nutrients, heavy metals and organic micropollutants are expected.

Global-scale quantitative scenarios of pollutant emissions tend to focus on nitrogen, and the range of plausible futures is large. The scenarios of the Millennium Ecosystem Assessment expect global N-fertilizer use to reach between 110 and 140 Mt by 2050 as compared to 90 Mt in 2000 (Millennium Ecosystem Assessment 2005). In three of the four scenarios, total N-load increases at the global scale, while in the TechnoGarden scenario, which is similar to the IPCC SRES scenario B1, there is a reduction of atmospheric N-deposition as compared to today, so that the total N-load to the freshwater system decreases. In developed countries, diffuse emissions of nutrients and pesticides from agriculture will continue to be an important water quality issue, while these emissions are very likely to increase in developing countries.

The most important drivers of domestic and industrial water use are: population and economic development but also changing societal views on the value of water. This refers to the priority of domestic and industrial water supply over irrigation water supply and the extended application of water-saving technologies and water pricing. In regions with restricted piped water supply, the projected increases in per capita GDP (Chapter 2) will lead to increased per-capita domestic water use, while in OECD countries, the impact of water-saving technologies will be dominant. In all four Millennium Assessment scenarios, per-capita domestic water use in 2050 is rather similar in all world regions, around 100 m^3/yr (the European average in 2000), which implies a very strong increase in Sub-Saharan Africa (by a factor of 5, approximately) and smaller increases in other world regions except OECD where per capita domestic water use declines (Millennium Ecosystem Assessment 2005). The range of plausible futures of the drivers of irrigation, domestic and industrial water use is large (Alcamo *et al.* 2003; Alcamo *et al.* 2000; Seckler *et al.* 1998; Vörösmarty 2000).

According to an FAO projection of agriculture in developing countries, the developing countries (with 75% of the global irrigated area) are likely to expand their irrigated area by 2030 with the rate of increase 0.6%/yr, while the cropping intensity of irrigated land will increase from 1.27 to 1.41 (Bruinsma 2003). Most of this expansion will occur in already water-stressed areas, such as South Asia, Northern China, Near East and North Africa. On average, irrigation water use efficiency (ratio of consumptive water use to water withdrawal) is assumed to increase from 0.38 to 0.42. In all four scenarios of the Millennium Assessment, future extension of irrigated area is assumed to be much smaller than in the FAO projection, with global growth rates between 0 and 0.18%/yr between 1997 and 2050 (Millennium Ecosystem Assessment 2005). After 2050, irrigated area stabilizes or slightly declines in all scenarios except Global Orchestration. (which is similar to the IPCC A1 scenario).

3.4 Key future impacts and vulnerabilities

3.4.1 Surface waters

Changes in river flows as well as lake and wetland levels due to climate change depend primarily on changes to the volume and timing of precipitation and, crucially, whether precipitation falls as snow or rain. Changes in temperature, energy availability, atmospheric humidity and wind speed affect potential evaporation, and this can offset small increases in precipitation and exaggerate further the effects on surface waters of decreases in precipitation.

Since the TAR, about 100 studies of climate change effects on river flows have been published in the international literature, and many more studies have been reported in the grey literature. However, studies still tend to be heavily focussed towards Europe, North America, and Australasia. Virtually all studies use a catchment hydrological model driven by scenarios based on climate model simulations, with a number of them using SRES-based scenarios (e.g. Hayhoe *et al.* 2004; Zierl & Bugmann 2005; Kay *et al.* 2005). A number of global-scale assessments (e.g. Manabe *et al.* 2004; Nohara *et al.* 2005) use directly climate model simulations of river runoff, but estimated changes are dependent on the ability of the climate model to simulate baseline runoff reliably.

Advances since the Third Assessment Report have focused on exploring the effects of different ways of downscaling from the climate model scale to the catchment scale (e.g. Wood *et al.* 2004), the use of regional climate models to create scenarios or drive hydrological models (e.g. Arnell *et al.* 2003; Shabalova *et al.* 2003; Andreasson *et al.* 2003; Payne *et al.* 2004, Fowler & Kilsby 2005; Kay *et al.* 2005; Prudhomme & Davies, submitted), ways of applying scenarios to observed climate data (Drogue *et al.* 2004), and the effect of hydrological model uncertainty on estimated impacts of climate change (Arnell 2005). In general, these studies have shown that different ways of creating scenarios from the same source (a global-scale climate model) can lead to substantial differences in the estimated effect of climate change, but that hydrological model uncertainty may be smaller than errors in the modelling procedure or differences in climate scenarios (Jha *et al.* 2004; Arnell 2005; Kay *et al.* 2006; Wilby 2005). However, the hydrological model uncertainty depends on the catchment in question, the type of hydrological model, flow diagnostic and future time horizon.

Figure 3.3 gives an indication of the effects of future climate change on average annual river runoff across the world, under the A2 emissions scenario and different climate models (Arnell 2003). There are some generally consistent patterns of change – increases in high latitudes and the wet tropics, and decreases in mid-latitudes and some parts of the dry tropics – the magnitude of change varies between climate models, and in some regions – such as southern Asia – runoff could either increase or decrease. Under B2 emissions, patterns of change are similar and only by the 2080s there is a clear difference in magnitudes, with runoff changes for B2 smaller than for A2.

Figure 3.3 shows that the climate change signal is large relative to natural decade-to-decade variability across most of the world under A2 emissions. At a more local scale, studies have shown that climate change effects may be visible (and implicitly statistically detectable) as early as in the 2020s (Dettinger *et al.* 2004), particularly where changes in temperature are producing changes in the timing of streamflows. Where hydrological regimes are more sensitive to changes in precipitation than to changes in temperature, it is possible that the effects of climate change will take longer to detect.

A very robust finding of hydrological impact studies is that warming leads to changes in the seasonality of river flows where much winter precipitation currently falls as snow (Barnett *et al.* 2005). This has been found in the European Alps (Eckhardt & Ulbrich 2003; Andreasson *et al.* 2004; Jasper *et al.* 2004; Zierl & Bugmann 2005), the Himalayas (Singh 2003; Singh & Bengtsson 2004), western North America (Loukas *et al.* 2002a, b; Stewart *et al.* 2004; Payne *et al.* 2004; Vanrheenen *et al.* 2004; Dettinger *et al.* 2004; Knowles & Cayan 2004; Leung *et al.* 2004; Christensen *et al.* 2004; Hayhoe *et al.* 2004; Maurer & Duffy 2005; Kim 2005), central North America (Stone *et al.* 2001; Jha *et al.* 2004) and eastern North America (Frei *et al.* 2002; Chang 2003; Dibike & Coulibaily 2005) and Scandinavia and Baltic regions (Andreassan *et al.* 2004; Graham 2004; Bergstrom *et al.* 2001). The effect is greatest at lower elevations (where snowfall is more marginal: Jasper *et al.* 2004; Knowles & Cayan 2004), and in many studies brings forward the peak flow season by at least a month. Winter flows increase and summer flows decrease.

Many rivers draining glaciated regions, particularly in the Himalaya-Hindu Kush and the South American Andes, are sustained by glacier melt during the summer season (Barnett *et al.* 2005; Singh & Kumar 1997; Mark & Seltzer 2003). Warmer temperatures generate increased glacier melt, although this may be offset by increased precipitation. Schneeberger *et al.* (2003) simulated reductions in the mass of a sample of Northern Hemisphere glaciers of up to 60% by 2050. As these glaciers retreat due to global warming (Chapter 1), river flows are increased in the short term but the contribution of glacier melt will gradually fall over the next few decades.

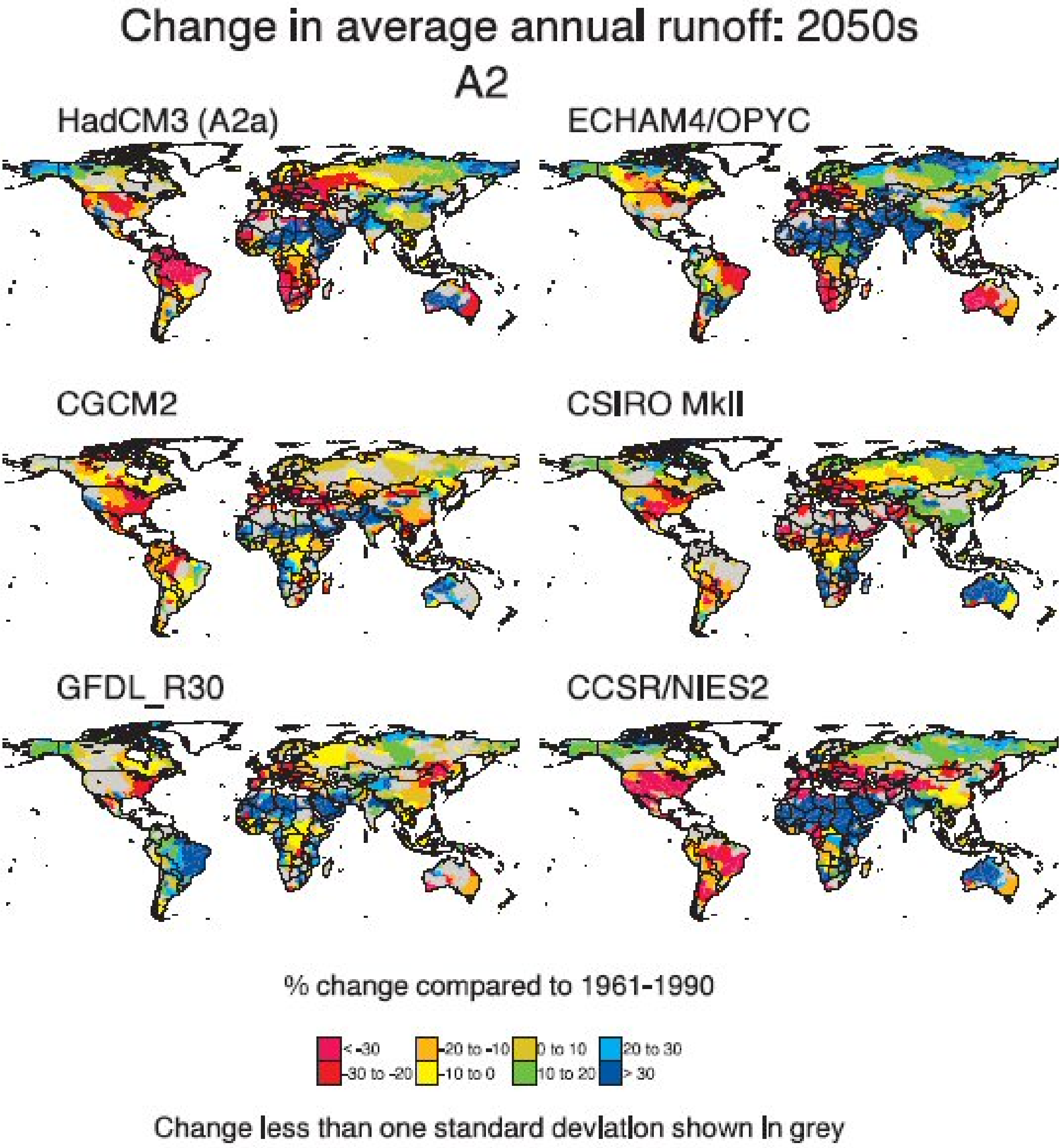


***Figure 3.3:** Change in average annual runoff as simulated across the world under the SRES A2 emissions scenario and different climate models (Arnell 2003).*

In regions with little or no snowfall, changes in runoff are dependent much more on changes in rainfall than on changes in temperature. A general conclusion from studies in many rain-dominated catchments (Boorman 2003; Booij 2005; Menzel & Burger 2002; Burlando & Rosso 2002; Arnell 2003b; 2004; Evans & Schreider 2002) is that flow seasonality increases, with higher flows in the peak flow season and either lower flows during the low flow season or extended dry periods. In most case studies there is little change in timing of peak or low flows, although an earlier onset in the East Asian monsoon would bring forward the season of peak flows in China (Bueh *et al.* 2003).

Changes in lake levels are determined primarily by changes in inflows and precipitation onto the lake, and to a lesser extent by changes in evaporation from the lake. Impact assessments of the Great Lakes suggest changes in water levels of between -1.38m and +0.35m by the end of the 21st century (Lofgren *et al.* 2002; Schwartz *et al.* 2004). Levels in Lake Victoria, in contrast, are projected under one scenario to fall by the 2030s and then rise by the 2080s, reflecting the interplay of evolving changes in rainfall and evaporation (Tate *et al.* 2004).

Model studies show that feasible land-use changes have a small effect on annual runoff as compared to climate change in the Rhine basin (Pfister *et al.* 2004), south east Michigan (Barlage *et al.* 2002), Pennsylvania (Chang 2003) and central Ethiopia (Legesse *et al.* 2003). In other areas, however, such as south east Australia (Herron *et al.* 2002) and southern India (Wilk & Hughes 2002), land-use and climate-change effects may be more similar. In the Australian example, climate change has the potential to exacerbate considerably the reductions in runoff caused by afforestation.

Accounting for the effects of CO_2 enrichment on river flow requires the incorporation of a vegetation model into a hydrological model. A small number of models now do this (Gerten *et al.* 2004; Gordon & Famiglietti 2004; Rosenberg *et al.* 2003, but usually are at the GCM (and not catchment) scale). Recently, it has been found that the increase in global mean runoff under a doubled-CO_2 climate was approximately 50% greater when the direct effects of CO_2 on transpiration (“physiological forcing”) were included.(Betts, submitted). The robustness of this was examined with an ensemble of 128 GCM simulations including sub-sets with and without CO_2 physiological forcing. The potential offsetting effect of increased plant growth was examined by the use of a dynamic global vegetation model (Cox 2001; Betts *et al.* 2004) and it was found that increased leaf area did not offset reduced stomatal conductance. In regions of decreased precipitation, the decrease in runoff was smaller when CO_2 physiological forcing was included. In regions of increased precipitation, CO_2 physiological forcing enhanced the runoff increase (Betts *et al.* 2006 submitted).

3.4.2 Groundwater

It is likely that millions of people will be increasingly use groundwater in the warmer future. However, there has been very little research on the impacts of climate change on groundwater, including the question how climate change will affect the important relation between surface waters and shallow aquifers which are hydraulically connected (Alley 2001). Both shallow and deep aquifers will be influenced by climate change, even though there will be a considerable delay in the case of very deep aquifers. Under certain circumstances (good hydraulic connection of river and aquifer, low groundwater recharge rates), changes in river stage influence groundwater levels much stronger than changes in groundwater recharge (Allen *et al.* 2004). Any changes in key climatic variables may significantly alter recharge rates for major aquifer systems and thus the sustainable yield of groundwater in the region. As a result of climate change, in many aquifers of the world the spring recharge retreats towards winter, and summer recharge declines. Climate change may lead to vegetation changes which also affects groundwater recharge. With increased frequency and the magnitude of floods, groundwater recharge may tend to increase in semi-arid and arid areas where heavy rainfalls and floods are the major sources of groundwater recharge. Bedrock aquifers in semi-arid regions are replenished by direct infiltration of precipitation into fractures and dissolution channels as well as by floods, while alluvial aquifers are mainly recharged by floods. Accordingly, an assessment of climate change impact on groundwater recharge in those areas requires to assess the impact of climate change on floods and inundation areas (Khiyami *et al.* 2005.

Future decreases of groundwater recharge and groundwater levels were projected for various climate

scenarios which predict less summer and more winter precipitation, using a coupled groundwater and soil model for a groundwater basin in Belgium (Brouyere *et al.* 2004). The impacts of climate change on a chalk aquifer in eastern England appear to be similar; in summer, groundwater recharge and streamflow will reduced by up to 50%, potentially leading to problems concerning water quality, groundwater withdrawals and hydropower generation (Eckhardt and Ulbrich 2003). Based on a historical analysis of precipitation, temperature and groundwater levels in a confined chalk aquifer in southern Canada, the correlation of groundwater levels with precipitation was found to be stronger than the correlation with temperature; however, with increasing temperatures, the sensitivity of groundwater levels to temperature increases (Chen *et al.* 2004), in particular where the confining layer is thin. For an unconfined aquifer located in the humid north-eastern U.S., climate change was computed to lead by 2030 and 2100 to a variety of impacts on groundwater recharge and levels, wetlands, water supply potential, and low flows, the sign and magnitude strongly depending on the climate model that was used to compute the groundwater model input (Kirshen 2002).
With respect to groundwater quality, climate change is likely to have a strong impact on coastal saltwater intrusion at the coast but also inland (Chen *et al.* 2004), as well as on the salinization of groundwater due to increased evapotranspiration. Sea-level rise leads to intrusion of saline water into the fresh groundwater in coastal aquifers and thus adversely affects groundwater resources. Any decrease in groundwater recharge will exacerbate the affect of sea level rise on salt water intrusion. For two small and flat coral islands off the coast of India, the thickness of the freshwater lens was computed to decrease from 25 m to 10 m and from 36 to 28 m, respectively, for a sea level rise of only 0.1 m (Bobba *et al. 200*0).

According to the results of a global hydrological model, groundwater recharge (when averaged globally), will increase less than total runoff (Döll 2005). While total runoff (groundwater recharge plus fast surface and subsurface runoff) was computed to increase by 9% between the climate normal 1961-1990 and the 2050s (for the ECHAM4 interpretation of the SRES A2 emissions scenario), groundwater recharge increases only by 2%. For all of the investigated four climate scenarios, computed groundwater recharge decreases dramatically by more than 70% in north-eastern Brazil, southwest Africa and along the south rim of the Mediterranean Sea (Fig. 3.4). In these areas of decreasing total runoff, the percent decrease of groundwater recharges is higher than the percent decrease of total runoff, which is due to the model assumption that in semi-arid areas, groundwater recharge only occurs if daily precipitation exceeds 10 mm. Regions with groundwater recharge increases of more than 30% until the 2050s include the Sahel, the Near East, Northern China, Siberia and the Western USA. There, rising groundwater tables might cause problems, e.g., in towns or agricultural areas (soil salinization, wet soils). A comparison of the four scenarios in Fig. 3.4. shows that lower emissions do not lead to less changes in groundwater recharge but that in some regions (e.g. Spain, Australia) the differences due to the two climate models are larger than the differences due to the two emissions scenarios.

3.4.3 Floods and droughts

The weight of observational evidence indicates an ongoing intensification of the water cycle (Huntington 2006). Using the Palmer Drought Severity Index (PDSI), Dai *et al.* (2004) concluded that very dry or very wet areas (with PDSI above +3 or below -3) have increased, globally, from 20% to 38% since 1972. Climate models suggest that the water cycle will further intensify, with possible consequences to extremes (Wetherald & Manabe 2002). The warmer climate increases risks of both floods and droughts (SPM WG1).

Yet there are a number of non-climatic factors influencing flood and drought impacts. Floods depend on such factors as precipitation intensity, volume, and timing, conditions of rivers and their drainage basins (e.g., presence of snow and ice, soil wetness, urbanization, dikes, dams, reservoirs). Human encroaching into flood plains increases the damage potential. The socio-economic impacts of droughts may arise from the interaction between the natural conditions and human factors, such as changes in land-cover, water demand and use. Excessive water withdrawals exacerbate the impact of drought. The 21st century, featuring further demographic growth, has been labelled as the age of water scarcity.

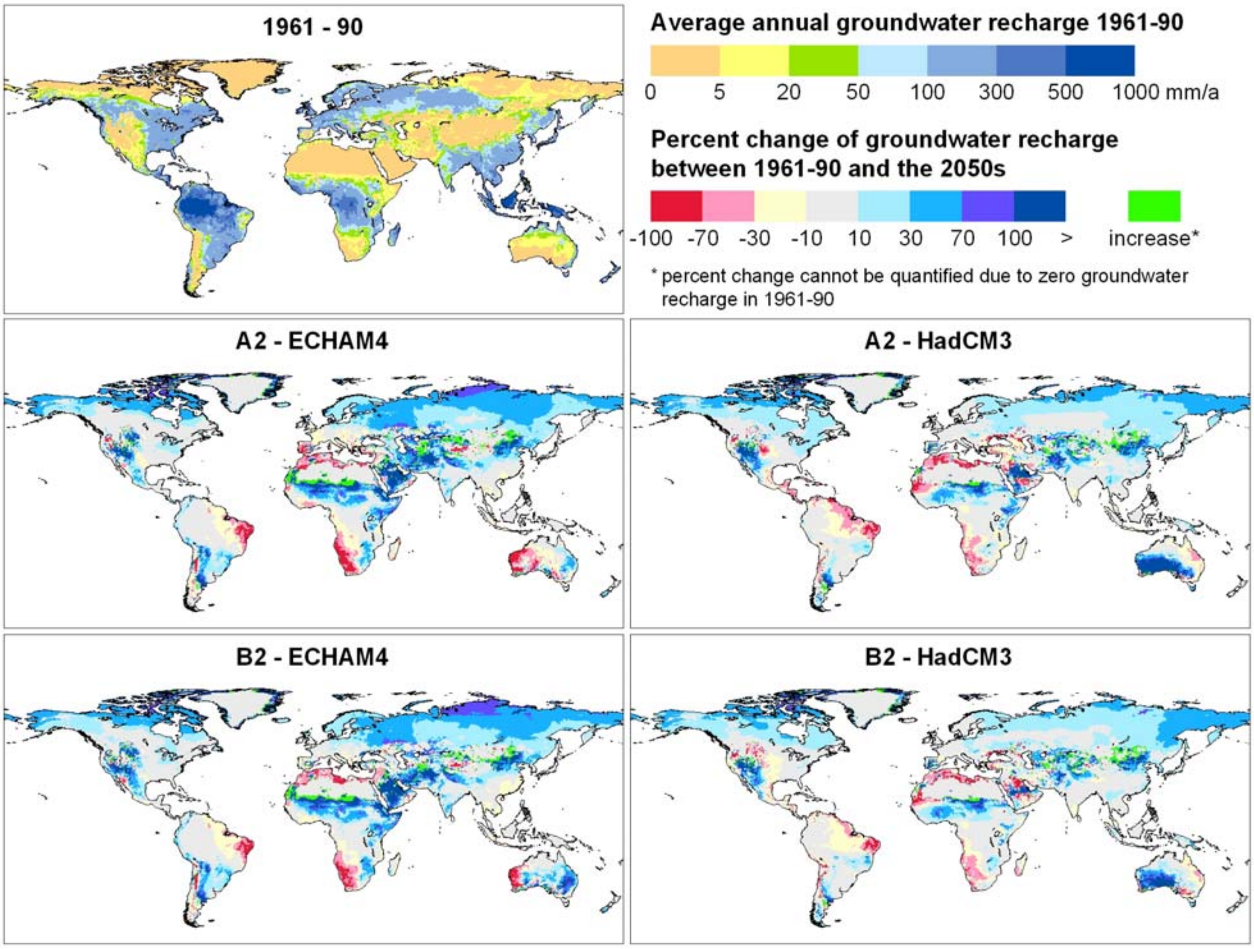


Figure 3.4: *Simulated impact of climate change on long-term average annual diffuse groundwater recharge. Percent changes of 30-year averages groundwater recharge between 1961-1990 and the 2050s (2041-2070), as computed by the global hydrological model WGHM, applying four different climate change scenarios (climate scenarios computed by the climate models ECHAM4 and HadCM3, each interpreting the two IPCC greenhouse gas emissions scenarios A2 and B2 (Döll 2005).*

Widespread increases in heavy precipitation events (e.g., number of 95th percentile events) have been observed, even in areas where there has been a reduction in total precipitation. These changes are associated with increased water vapour in the atmosphere arising from the warming of the world's oceans, especially in lower latitudes, and partly from the increasing land-surface drying. Increases have also been reported for rare precipitation events (e.g. 1 in 50 year return period), but only a few regions have sufficient data to assess such trends reliably (SPM WG1).

A robust result, consistent across model projections is that higher precipitation extremes in warmer climates are very likely to occur. Increase of proportion of heavy precipitation events is likely over many areas of the globe [high confidence, SPM WG1]. Increase of droughts over low-latitudes (and mid-latitude continental interiors in summer) is likely [moderate confidence, but sensitive to model land-surface formulation, SPM WG1].

Recent works on changes in precipitation extremes in Europe (Giorgi *et al.* 2004; Räisänen *et al.* 2004) agree that the intensity of daily precipitation events will predominantly increase. Extremes of daily precipitation in northern Europe and drought in southern areas of Australia will very likely increase [cf. WG1 Christensen & Hewitson 2007]. The number of wet days is projected to decrease (Giorgi *et al.* 2004), which leads to longer dry periods except in the winter of West and Central Europe. Increase of the number of days with intense precipitation has been projected in most of Europe, except for the south (Kundzewicz *et al.* 2006). This matches the findings of much larger projected increase in the frequency than in the magnitudes of precipitation extremes, particularly over northern Europe, Australia and New Zealand. Large increase during the summer monsoon season is very likely over Arabian Sea, tropical Indian Ocean, northern Pakistan and India, Bangladesh and Myanmar, South China, Korea and Japan [SPM WG1].

Even if the summer precipitation mean is projected to decrease over nearly all Europe, the behaviour of precipitation extremes is very much different. Increases in precipitation extremes are projected over much of the areas where means are likely to decrease (Christensen & Christensen 2003, Kundzewicz *et al.* 2006).

Decrease in summer precipitation in Southern Europe, accompanied by growing temperatures, which enhances evapotranspiration, would inevitably lead to reduced summer soil moisture (cf. Douville *et al.* 2002) and more frequent and more intense droughts. Annual rainfall is very likely to decrease in much of North Africa and Northern Sahara, exacerbating drought risk (cf. Christensen & Hewitson 2007).

As temperatures rise, the likelihood of precipitation falling as rain rather than snow increases, especially in fall and spring in areas with temperatures near to 0^{o}C [SPM WG1]. Snowmelt is projected to be earlier and less abundant, and this may lead to rising risk of droughts in snowmelt-fed basins in summer and autumn, when demand is highest (Barnett *et al.* 2005).

With more than one-sixth of the Earth's population relying on glaciers and seasonal snow packs for their water supply, the consequences of projected changes for future water availability, predicted with high confidence and already diagnosed in some regions, are likely to be adverse and severe (Barnett *et al.* 2005). In the Andes, glacial meltwater supports river flow during the long dry season. The rapid shrinkage of glaciers, e.g. in Bolivia, Ecuador and Peru (cf. Coudrain *et al.* 2005) may lead to droughts adversely affecting millions of people and ecosystems with rare and endemic species. Rapid melting of glaciers can lead to flooding of rivers and to the formation of glacial meltwater lakes, which may pose the serious threat of dynamic outburst floods (cf. Coudrain *et al.* 2005).

In many parts of Europe, significant changes in flood or drought risk are expected under IPCC IS92a scenario (similar to SRES A1) for the 2020s and the 2070s (Lehner *et al.* 2005). The regions most prone to a rise in flood frequencies are northern to north-eastern Europe, while southern and south-eastern Europe shows significant increases in drought frequencies. This is the case for climate change as computed by both the ECHAM4 and the HadCM3 model (Fig. 3.5). Both models agree in their estimates that a 100-year drought of today's magnitude would return more frequently than every 10 years in parts of Spain and Portugal, Western France, the Vistula Basin in Poland, and Western Turkey. Studies in Britain indicate a decrease in peak floods by 2080s (Kay *et al.* 2005) despite an overall increase in rainfall.

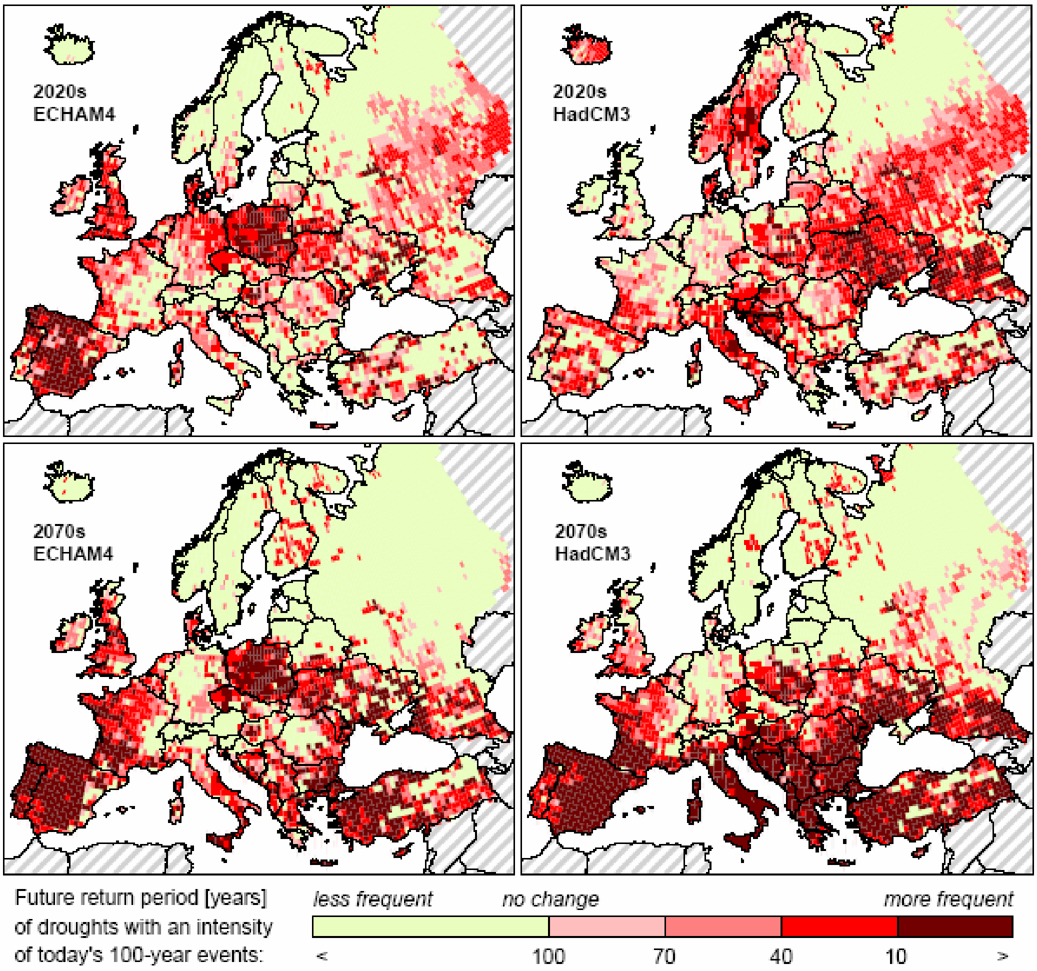


Figure 3.5: *Change in recurrence of 100-year droughts, based on comparisons between today's climate and water use (1961-90) and simulations for the 2020s and 2070s (ECHAM4 and HadCM3 climate models, emissions scenario IS92a and a business-as-usual water use scenario). Values calculated with the model WaterGAP 2.1 (Lehner 2005).*

Results of a recent study (Reynard *et al.* 2005) show that estimates of future changes in flood frequency across the UK are now noticeably different than in earlier (pre-TAR) assessments, when increasing frequencies under all scenarios were projected. Depending which GCM is used, and catchment characteristics and location, the impact of climate change on the flood regime (magnitude and frequency) can be both positive or negative, highlighting the uncertainty still remaining in climate change impacts (Reynard *et al.* 2004).

Palmer & Räisänen (2002) analyzed the modelled differences between the control run and an ensemble with transient increase in CO_2 and calculated around the time of CO_2 doubling. A considerable increase of the risk of a very wet winter in Europe and a very wet monsoon season in Asia was found. This would have consequences to flood hazard. The modelling results indicate that the probability of total boreal winter precipitation exceeding two standard deviations above normal will (even five- to seven-fold) increase considerably over large areas of Europe.

Milly *et al.* (2002) demonstrated that for 15 out of 16 large basins worldwide, the control 100-year flood (in monthly time-scale) is projected to be exceeded more frequently as a result of CO_2 quadrupling. In some areas, what is given as a 100-year flood now (in the control run), is projected to occur much more frequently, even every 2 to 5 years, albeit a large uncertainty in these projections is recognized.

Future changes in the joint probability of extremes have been considered, such as soil moisture and flood risk (Sivapalan *et al.* 2005) and or fluvial flooding and tidal surge (Svensson and Jones 2005).

Impacts of extremes on human welfare are likely to occur disproportionately in countries with low adaptation capacity (Manabe *et al.* 2004). Up to 20% of the world population live in river basins that are likely to be affected by increased flood hazard in the course of global warming (Kleinen & Petschel-Held 2006).

3.4.4 Water quality

Unless water management measures are taken, higher water temperature and variation in runoff will produce adverse changes in water quality affecting human health, ecosystems and water uses (Patz 2001; O'Reilly *et al.* 2003; Lehman 2002 and Hurd *et al.* 2004).

Higher water temperatures have been found to transfer volatile and semi-volatile compounds (ammonia, mercury, PCBs, dioxins, pesticides) from water bodies to the atmosphere [Medium confidence] (Schindler 1997; Schindler 2001).

As a result of a lowering of the water level, sediments from the bottom may be re-suspended liberating compounds with negative effects on water supplies [Medium Confidence](Lofgren *et al.* 2002). As a result of more rainfall, suspended solids (or turbidity) will increase in lakes and reservoirs due to soil fluvial erosion [High confidence] (Leemans and Kleidon 2002) and different pollutants will be introduced with varying effects depending on local conditions (Mimikou *et al.* 2000; Bouraoui *et al. 200*4; Neff *et al.* 2000). Socioeconomic factors might play a determining role as to the type and extent of the effects (Abler *et al.* 2002; Fisher 2000).

Higher water temperatures in surface water bodies will promote algal blooms [High confidence] (Hall *et al.* 2002; Kumagai *et al.* 2003) and increase the bacteria and fungi content [Medium confidence] (Environment Canada 2001). Under this situation, bad odour and taste might be produced in chlorinated drinking water and, in some cases, toxins may be present (Moulton and Cuthber 2000; Robarts *et al.* 2005). Moreover, even with enhanced P removal in wastewater treatment plants, algal growth will increase over the long term, due to rising water temperature (Wade *et al.* 2002). Due to the high cost and the intermittent nature of the problems created by algal blooms, it is considered that water utilities will be unable to solve this problem with the available technology (Environment Canada 2001). Increasing nutrients and sediments due to higher runoff coupled with lower water levels will produce chemical and biological reactions in lakes and reservoirs that negatively affect water quality (Hamilton *et al.* 2001). It is foreseen that strong changes could render a source unusable unless the water treatment plants are adequately modified (Environment Canada 2004).

In regions where rainfall is expected to increase, pollutants (pesticides, organic matter, heavy metals, etc.) will be increasingly washed from soils to water bodies (Fisher 2000; Environment Canada 2001; Environment Canada 2004; Borman 2003). Higher runoff is expected to mobilize fertilizers and pesticides to water bodies in regions, where their application time and a low vegetation growth coincide with the period when runoff increase is predicted [Medium confidence] (Soil and Water Conservation Society 2003). Also, acidification in rivers and lakes is expected to increase [Medium confidence] as a result of runoff carrying acidic atmospheric deposition (Gilvear *et al.* 2002; Ferrier and Edwards 2002; Soulsby *et al.* 2002).

In rivers next to the ocean and also on inlands where streamflow is expected to decrease, salinity will increase (Beare and Heaney 2002; Bell and Heaney 2001; Robarts *et al.* 2005; Williams 2001; Pittock 2003). In this latter study, for the Murray arling Basin in Australia, using two mid-range SRES scenarios, the salt concentration in the tributary rivers above irrigation areas is projected to increase by 13-19% by 2050 and 21-72% by 2100. Secondary salinization of water (due to human disturbance of the natural salt cycle) will also threaten a large number of people relying on water bodies already suffering from primary salinization (Williams 2001). In areas where the climate becomes hotter and drier, human activities to counteract the increased aridity (*e.g.* more irrigation, diversions and impoundments) will exacerbate the causes of secondary salinization (Williams 2001). Water salinization is expected to be a major problem in areas where: (a) larger precipitation minus evaporation is present; (b) saline intrusion increases, (c) higher evapotranspiration occurs, or (d) higher vegetative growth absorbs freshwater from soil leaving salts that are washed down during infiltration to groundwater (Bobba *et al.* 2000; Loáiciga 2003; Han *et al.* 1999; Ministry for the Environment 2002; Williams 2001; Chen *et al.* 2004).

Increase in extreme rainfall events, which is projected for the changing climate, will cause waterborne diseases to rise (Hall *et al.* 2002; D'Souza *et al.* 2004; Hijioka *et al.* 2002). Also some studies point out that in regions suffering from droughts, water quality (Environment Canada 2004; Patz 2001), is expected to decrease due to a greater incidence of diarrheic and other diseases producing an endless cycle. However, there are no projections of biological characteristics of water supplies or wastewater. This is a critical issue for developing countries where the biological quality of water and wastewater is already notably poorer than that of developed countries (Maya *et al. 200*3; WHO 2004; Lipp *et al.* 2001; Jimenez 2003). Hence, climate change will be an additional stressor causing an extra burden that is difficult to overcome (Pachauri 2004; Magadza 2000; Kashyap 2004). Regrettably, there are no studies analysing the impact of climate change on biological water quality from the developing countries perspective, i.e. considering (a) the organisms' presence and pathways typical of developing countries; (b) the effect of more intense use of wastewater to produce food; (c) the increase of *Helminthiases* diseases endemic only in developing countries where low quality water is used for irrigation; and (d) the increased distribution of low water quality due to an increasingly intermittent operation of water networks during droughts (WHO/UNICEF 2000).

Even in places where water and wastewater treatment plants already exist, the greater presence of a wider variety of micro-organisms will pose a threat because facilities are not necessarily designed to deal with them. As an example, *Cryptosporidium* outbreaks following extreme rainfalls have forced some developed countries to adopt an additional filtration step in drinking water plants representing a 20-30 % increase in the operating cost (AWWA 2005) but this is still not a universal practice.

Water quality modifications could also be observed as result of: (a) more water impoundments for hydropower (Kennish 2002; Environment Canada 2004); (b) storm water drainage operation and sewage disposal disturbances in coastal areas due to a rise in the sea level (Haines *et al.* 2000); (c) increasing water withdrawals from low quality sources; (d) greater pollutant loads due to increased infiltration rates to aquifers or higher runoff to surface water; (e) water infrastructure malfunctioning during floods (GEO-LAC 2003; DFID 2004); (f) overloading water and wastewater treatment plants' capacity during extreme rainfall (Environment Canada 2001); and (g) an increased amount of polluted storm water..

In areas where precipitation, river flow, lake water level and groundwater recharge will decrease, water quality will also decrease due to a lower dilution effect. The exploitation of lower water quality may be necessary (Environment Canada 2004), also in areas already facing problems with arsenic and fluoride (UN 2003). A recent study (BGS and DHPE 2001 cited in UN 2003) suggests that Bangladesh is grappling with the largest mass poisoning in history, potentially affecting between 35 and 77 million of the country's 130 million inhabitants. It is estimated that the health impact of naturally occurring fluoride is more widespread than that of arsenic. In eight countries alone there are 30 million people suffering from chronic fluorosis (UN 2003).

With increasing population and wealth, a more efficient use of water (including reuse) will be needed. At present, due to lack of water and sanitation, it is estimated that at least one-tenth of the world's population consumes crops irrigated with wastewater (Smit and Nasr 1992) mostly in developing countries located in Africa, Asia and Latin America where warming is expected (DFID 2004). Since agriculture is the activity responsible for 70 % of total amount of the water withdrawals worldwide, (WRI 2001), and considering the convenience of recycling nutrients (Jimenez and Garduño 2001), it is important to be aware of the health and environment risks caused by reusing low quality water.

Summing up the vulnerabilities related to climate change and water quality, one can state that for developing countries they are basically related to a lack of information relevant to their needs as well as their institutional weakness in responding to a changing environment. For the world as a whole, vulnerabilities are related not only to the need to have information about the effects of new chemicals (their sources, occurrence, concentrations, survival and transportation) on health and ecosystems (Environment Canada 2001), but also the need to respond proactively to environmental changes despite the information gap. The effects of climate change on water quality may involve re-thinking of effluents disposal strategy (because warmer water bodies have less self-purification capacity), the design of water and wastewater treatment plants, acting efficiently even during extreme climatic conditions, and the way of reusing and recycling water (Environment Canada 2004; Luketina and Bender 2002; Patrinos and Bamzai 2005). Finally, it was shown that in order to give the public the required level of protection, protocols for the setting of standards and their enforcement need to be reconsidered (Crane *et al.* 2005).

3.4.5 Erosion

All studies on soil erosion suggest that increased rainfall amounts and intensities will lead to greater rates of erosion. Thus, if rainfall amounts and intensities increase in some parts of the world as expected, erosion will also be on the increase, unless amelioration measures are taken. While soil erosion rates are expected to change in response to changes in climate for a variety of reasons, the most direct is the change in the erosive power of rainfall.

Nearing (2001) used output from the UK Hadley Centre model (HadCM3GGa1) and the Canadian Centre for Climate Modeling and Analysis model (CGCM1) and relationships between monthly precipitation and rainfall erosivity (the power of rain to cause soil erosion), developed by Renard and Freidmund (1994), to assess potential changes in rainfall erosivity in the United States. Predicted changes were significant and in many cases very large, but results between models differed both in magnitude and regional distributions. Zhang *et al.* (2005) used output from HadCM3GGa1 and a relationship based on the literature data of Wang and Jiao (1996) to assess potential changes in rainfall erosivity in the Yellow River Basin of China. Increases in rainfall erosivity by as much as 11 to 22% by the year 2050 were projected across the region.

Michael *et al.* (2005) projected potential increases in erosion on the order of 20 to 60% over the next five decades for two exemplary sites in Saxony, Germany, using the erosion model EROSION 2D (Schmidt 1990), and climate input data were based on regional downscaling methods of Enke

(2000, 2003).

Pruski and Nearing (2002b) simulated erosion for the 21st century at eight locations in the United States using the Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing 1995) modified for CO_2 effects on plant growth, using HadCM3GGa1 output for driving climate. The WEPP model incorporated the primary documented physical and biological mechanisms affecting erosion. Simulated cropping systems were corn and wheat. The results indicated a complex set of interactions between the several factors that affect the erosion process. Overall, these results suggested that where precipitation increases were projected, estimated erosion increased between 15 and 101%. Where precipitation decreases were projected by the GCM, the results were more complex due largely to interactions of plant biomass, runoff, and erosion, and either increases or decreases in overall erosion could occur.

Zhang and Nearing (2005) evaluated the potential impacts of climate change on soil erosion, surface runoff, and wheat productivity in central Oklahoma. Monthly projections were used from the Hadley Centre’s general circulation model, HadCM3, using scenarios A2a, B2a, and GGa1 for the periods of 1950–1999 and 2070–2099. While HadCM3-projected mean annual precipitation during 2070–2099 at El Reno, Oklahoma decreased by 13.6%, 7.2%, and 6.2% for A2a, B2a, and GGa1, respectively. Predicted erosion (except for the no-till conservation practice scenario) increased by 18–30% for A2a, remained similar for B2a, and increased by 67–82% for GGa1. The greater increases in erosion in GGa1 were attributed to greater variability in monthly precipitation as projected by HadCM3, which led to increased frequency of large storms. Results indicated that no-till (or conservation tillage) systems can be effective in reducing soil erosion under projected climates in central Oklahoma.

A more complex, but potentially dominant factor in the equation of erosion and climate change, is the potential for shifts in land use necessary to accommodate a new climatic regime (O’Neal *et al.* 2005). As farmers adapt cropping systems, the susceptibility of the soil to erosive forces will also change. Farmer adaptation may range from shifts in planting, cultivation, and harvest dates to changes in crop type (Southworth *et al.* 2000, 2002a, b; Pfeifer and Habeck 2002). Modelling results for the upper Midwest U.S. suggest that erosion will increase as a function of future land-use changes, largely because of a general shift away from wheat and corn towards soybean production. For 10 of 11 regions of the study area, predicted runoff increased from +10% to +310%, and soil loss increased from +33% to +274%, in 2040–2059 relative to 1990–1999. These results are the only examples that outline the potential magnitude of erosion rate changes that can occur with land-use shifts. Other scenarios would lead to different results. For example, improved conservation practices can greatly reduce erosion rates (Souchere *et al.* 2005), while clear cutting a forest during a "slash-and-burn" operation can change soil surface cover from near 100% to near 0%, which will have a huge negative impact on susceptibility to runoff and erosion.

In terms of implications of climate change for soil conservation efforts, a significant realization from recent scientific efforts is that conservation measures must be targeted to the extreme events more than ever before (Soil and Water Conservation Society 2003). Intense rainfall events contribute a disproportionate amount of erosion relative to total rainfall contribution, and this effect will only be exacerbated in the future as the frequencies of such storms are on the rise around the world.

Changes in water balance terms affect many geomorphic processes including slope stability, channel change, and sediment transport (Jones 1993a,b; Rumsby and Macklin 1994). There are also indirect consequences of geomorphic change for water quality (Dennis *et al.* 2003). Furthermore, hydromorphology is an influential factor of freshwater habitat.

3.5 Costs and other socio-economic aspects

Impacts of climate change will entail social and economic costs and benefits, which are difficult to determine. On top of uncertainties about the impacts of future climate change on freshwater systems, there are other compounding factors, including demographic, societal and economic developments that should be considered when evaluating the costs of climate change. There are the costs of damages and the costs of adaptation (to reduce or avoid damages).

Costs and benefits of climate change can be expressed in monetary or non-monetary units (for example the number of people that are negatively or positively affected by climate change). There are no global assessments of past or future monetary costs of climate change impacts on freshwater. At the national scale (for the USA), the economic impacts of climate-related changes related to water cannot be determined due lack of good data, and quantitative estimates of the potential economic impacts of future climate change are highly uncertain due to the uncertainties of both future climate change impacts and future economic conditions (Changnon 2005).

With respect to water supply, there are reasons to believe that the costs of climate change are likely to outweigh the benefits. One reason is that precipitation variability is very likely to increase, which will lead to more floods and droughts. Another reason is that water infrastructure, use patterns, and institutions have evolved to fit current conditions. Any substantial change in the frequency of floods and droughts or in the quantity and quality or seasonal timing of water availability will require adjustment that may be costly not only in monetary terms, but also in terms of lost use values and the need to manage potential conflicts among different interested groups (Miller *et al.* 1997). Hydrological changes may have impacts that are positive in some aspects and negative in others. For example, increased annual runoff may produce benefits for a variety of instream and out-of-stream water users by increasing renewable water resources, but may simultaneously generate harm by increasing flood risk, and damaging areas with a shallow water table. In such areas, a water table rise will disturb agricultural use and damage buildings in urban areas. For Russia, for example, the current annual damage caused by shallow water tables is estimated to be 5-6 billion USD (Kharkina 2004) and is likely to increase in the future. In addition, an increase of annual runoff may not lead to a beneficial increase of readily available water resources, if the additional runoff is concentrated during high flow season.

3.5.1 How will climate change affect the balance of water demand and water availability?

To evaluate how climate change will affect the balance among water demands and water availability, it is necessary to consider the entire suite of socially valued water uses and how the allocation of water across those uses is likely to change. Water is socially valuable not only for domestic uses, but also for its role in supporting aquatic ecosystems and environmental amenities – including recreational opportunities, and as a factor of production in irrigated agriculture, hydropower production, and other industrial uses (Young 2005). The social costs or benefits of any change in water availability, or will depend on how the change affects each of these potentially competing human water demands. Changes in water availability will depend on changes in the volume, variability and seasonality of runoff, as modified by the operation of existing water control infrastructure and investments in new infrastructure. The institutions that govern water allocation will play a large role in determining the overall social impacts of a change in water availability, as well as the distribution of gains or losses across different sectors of a society. Institutional settings differ significantly both across and within countries, often resulting in substantial differences in the efficiency, equitability and flexibility of water use and infrastructure development (Wichelns *et al.* 2002; Saleth and Dinar 2004; Easter and Renwick 2004; Orr and Colby 2004; Svendsen 2005).

In addition, the quantity of water is not the only important variable. Changes in water quality and temperature can have substantial impacts on urban, industrial and agricultural use values as well as on aquatic ecosystems. For urban water uses, degraded water quality can add substantially to purification costs. Increased precipitation intensity may periodically result in increased turbidity and nutrient and pathogen loadings to surface water sources. The water utility serving New York City has identified heavy precipitation events as one of its major climate-change related concerns because such events can raise turbidity levels in some of the city's main reservoirs up to 100 times the legal limit for source quality at the utility's intake, requiring substantial additional treatment and monitoring costs (Miller and Yates 2006).

Water demand

There are many different types of water demands. Some of these compete directly with one another in that water consumed by one sector is no longer available for other uses. In other cases, a given unit of water may be used and reused several times as it travels through a river basin – for example, providing benefits to instream fisheries, hydropower generators and domestic users in succession. Climate change will likely alter the desired uses of water (demands) as well as actual uses (those demands in each sector that are actually met, given other competing uses of the resource). Because the availability of water for each type of use may be affected by other competing uses of the resource, a complete analysis of effects of climate change on human water uses should consider cross-sector interactions, including intentional transfers of the use of water from one sector to another. For example voluntary water transfers, generally from agricultural to urban or environmental uses are becoming increasingly common in the Western United States, and can be expected to play a role in facilitating adaptation to climate change (Easter *et al.* 1998; Miller *et al.* 1997).

Irrigation water withdrawals account for almost 70% of global water withdrawals and 90% of global consumptive water use (the water fraction that evapotranspires during use) (Shiklomanov 2003). Of all sectoral water demands, the irrigation sector will be affected most strongly by climate change. In areas facing water scarcity, changes in irrigation water use will be driven by the combined effects of change in irrigation water demand, changes in demands for higher values uses (e.g. for urban areas) and changes in availability.

Higher temperatures and increased variability of precipitation will, in general, lead to an increased irrigation water demand, even if the total precipitation during the growing season remained the same. Due to increased atmospheric CO_2 concentrations, water use efficiency of plants will increase, so that the ratio of water input per unit of crop yield increases. However, in hot regions like Egypt the ratio may even decline as yields decrease due to heat stress (cf. Chapter 5). There are no global-scale studies which attempt to quantify the influence of all these climate-change related factors on irrigation water use; only the impact of climate change on optimal growing periods and yield-maximizing irrigation water use has been modelled assuming no change in irrigated area and climate variability (Döll 2002; Döll 2003). Applying the IPCC A2 and B2 emission scenarios as interpreted by two climate models, it was found that the optimal growing periods could significantly shift in many irrigated areas. Net irrigation requirements of China and India, the countries with the largest irrigated areas worldwide, change by +2% to +15% and by -6% to +5% for the year 2020, respectively, depending on emissions scenario and climate model. Global net irrigation requirements increase by 1-3% until the 2020s and by 2-7% until the 2070s. The highest increases of global net irrigation requirements result from a climate scenario that is based on the B2 emissions scenario (with lower emissions than the A2 scenario). On the national scale, some integrative studies exist; two modelling studies on adaptation of the agricultural sector to climate change in the USA (i.e. shifts between irrigated and rainfed production) foresee a decrease in irrigated areas and withdrawals beyond 2030 for various climate scenarios (Reilly 2003; Thomson 2005). This is related to a declining yield gap between irrigated and rainfed agriculture caused by yield reductions of irrigated crops due to higher temperatures or yield increases of rainfed crops due to more precipitation. These studies did not take into account the increasing variability of daily precipitation such that rainfed yields are probably overestimated. In a study of corn irrigation in Illinois under profit-maximizing conditions, it was found that a 25% decrease of annual precipitation had the same effect on irrigation profitability as a 15% decrease combined with a doubling of the standard deviation of daily precipitation (Eheart 1999). This study also showed that the effect of precipitation change on profit-maximizing irrigation water use is larger than the effect on yield-maximizing water use, and that a doubling of atmospheric CO_2 has only a small effect.

It is not clear whether future changes in irrigation water use will be affected more strongly by climate change than by demographic and socio-economic changes as there are very diverse scenarios of future irrigation extension. According to an FAO study in which the climate change impact was not considered (Bruinsma 2003), an increase in irrigation water withdrawals of 14% is foreseen until 2030 for the developing countries. In the four Millennium Assessment scenarios, however, increases at the global scale are much less than this value as irrigated areas are assumed to increase between 0 and 6 % only until 2030 and between 0 and 10 % until 2050. The overwhelming water use increases are likely to occur in the domestic and industrial sectors, with computed increases of total water withdrawals between 14 and 83% until 2050 (Millennium Ecosystem Assessment 2005). This is based on the idea that the value of water is much higher for domestic and industrial uses, which is particularly true under conditions of water stress.

The increase of household water demand (via garden watering) and industrial water demand due to climate change will be rather small in most areas, e.g. less than 5% until the 2050s at selected locations (Downing 2003; Mote 1999). An indirect but small secondary effect is the increased electricity demand for cooling of buildings which will tend to increase water withdrawals for cooling of thermal power plants (cf. Chapter 7). A statistical analysis of water use in New York City showed that above 25°C daily per-capita water use increases by 11 litres per 1°C (Protopapas 2000).

Water availability for aquatic ecosystems

Of all ecosystems, freshwater ecosystems will have the highest proportion of species threatened with extinction due to climate change (Millennium Ecosystem Assessment 2005). In cold or snow-dominated river basins, atmospheric temperature increases do not only affect freshwater ecosystems via the warming of water (cf. Chapter 4) but also by causing water flow alterations. In northern Alberta, Canada, for example, a decrease of ice-jam flooding will lead to a loss of aquatic habitat (Beltaos 2006). Where river discharges decrease seasonally, negative impacts on both freshwater ecosystems and coastal marine ecosystems can be expected. Atlantic salmon in northwest England will be affected negatively by climate change, as in the 2080s (SRES A2 scenario), suitable flow depths during spawning time, which occur all the time now, will only exist over 94% of the time (Walsh 2006). Such changes will have implications for ecological flow management and the compliance with the EU Habitats Directive. In the case of decreased discharge in the Western USA, the Sacramento and Colorado River deltas could experience, until 2050, a dramatic increase in salinity and subsequent ecosystem disruption, and the Columbia River system will be faced with the choice of either spring and summer releases for salmon runs or summer and fall hydroelectric power production. Extinction of some salmon species due to climate change in the Pacific Northwest may take place regardless of water policy (Barnett 2004).

Not only freshwater ecosystems will be influenced by climate-related changes in freshwater availability. Changed freshwater inflows into the ocean will lead to changes in turbidity, salinity, stratification and nutrient availability, all of which affect estuarine and coastal ecosystems (Juric 2005). While increased river discharge of the Mississippi would increase the frequency of hypoxia in the Gulf of Mexico, increased river discharge into the Hudson Bay would lead to the opposite (Justic 2005). The frequency of bird-breeding events in the Macquarie Marshes in the Murray-Darling basin in Australia will decrease with reduced streamflow, as breeding of the colonially nesting water birds requires a certain minimum annual flow; climate change and reforestation can contribute equally to a decrease of river discharge, but before 2070 the largest impact can be expected from a shift in rainfall due to decadal-scale climate-variability (Herron 2002).

Water availability for socio-economic activities

Climate-change induced changes in river discharge are likely to have an important impact on water availability for instream water use, in particular for electricity production by hydropower and navigation. According to results of a macro-scale hydrological model for Europe, electricity production potential of hydropower plants existing at the end of the 20th century will increase, until the 2070s (IS92a emissions), by 15-30% in Scandinavia and Northern Russia and decrease by 20-50% and more in Portugal, Spain, Ukraine, Bulgaria and Turkey (Lehner 2005). For the whole of Europe, hydropower potential shows a decrease of 7-12% until the 2070s. Increased flood periods in the future will disrupt navigation more often, and low flow conditions that restrict loading of ships may increase, for the Rhine river, from 19 days under current climate conditions to 26-34 days in the 2050s (depending on the climate model) (Middelkoop 2001).

Water availability for withdrawal is a function of both runoff and technical water supply infrastructure (reservoirs, pumping wells, distribution networks etc.). Safe access to drinking water depends more on the level of technical water supply infrastructure than on the level of runoff. However, it is generally easier to provide access to drinking water in regions with high runoff than in those of low runoff so that it can be assumed that the goal of improved safe access to drinking water (a Millennium Development Target) will be harder to achieve in regions where runoff will decrease due to climate change. Besides, climate change leads to additional costs for the water supply sector e.g. due to changing water levels affecting water supply infrastructure, which might decrease the possibilities for extending the water supply services to more people.

Climate change-induced changes of the seasonal runoff regime and the inter-annual runoff variability can be as important for water availability as changes in the long-term average annual runoff if water is not withdrawn from large groundwater bodies or reservoirs. People living in snowmelt-fed basins experiencing decreasing snow storage in winter, may be negatively affected by decreased river flows in the summer and autumn (Barnett 2005). The Rhine, for example, might suffer from a reduction of summer low flows of 5-12% by the 2050s which will negatively affect water supply in particular for thermal power plants (Middelkoop 2001). Studies for the Elbe River Basin showed that actual evapotranspiration is projected to increase by 2050 (Krysanova and Wechsung 2002), while river flow, groundwater recharge, crop yield, and the diffuse-source pollution are likely to decrease (Krysanova *et al.* 2005). Investment and operation costs for additional wells and reservoirs which are required to guarantee reliable water supply under conditions of climate change have been estimated for China, and this cost is low in basins where the current water demand to water resources ratio, i.e. water stress, is low (e.g. Yangtze) and high where it is high (e.g. Yellow River) (Kirshen 2005). It is in the highly-stressed basins where the impact of climate change on water supply cost is highest, but also where the impact can be least reliably predicted due to the uncertain changes of runoff. As in the majority of basins an increase of water demand will occur in the future, the impact of climate change on water supply cost will increase in the future not only because of a stronger climate change but also due to a higher vulnerability to it.

Box 3.1: Cost of climate change in Okanagan, Canada.

The Okanagan region in British Columbia, Canada, is a semi-arid watershed of 8200 km^2 in area. Irrigation accounts for 78% of the total basin licensed water allocation, and water resources are unable to support extension in demand.

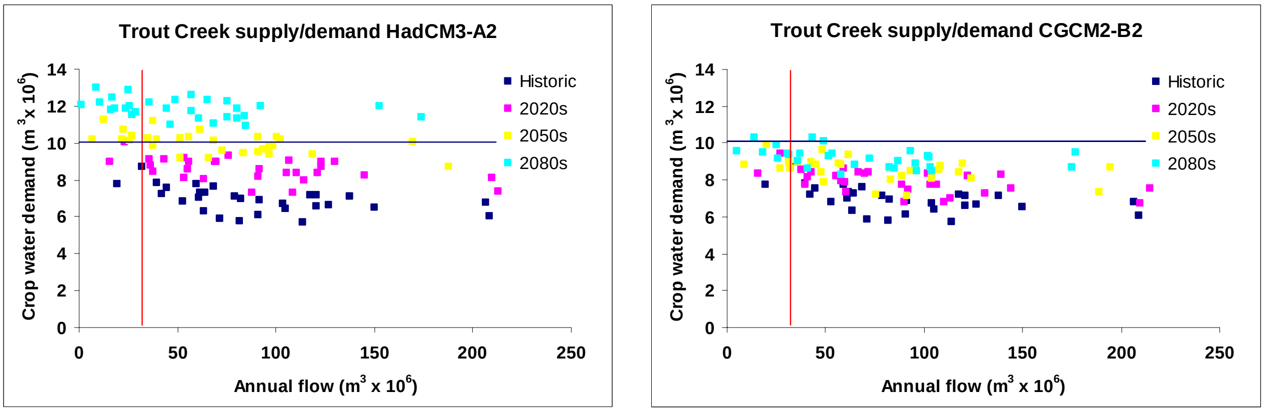


Figure 3.6: *Annual crop water demand and water supply for Trout Creek, Okanagan region, Canada, modeled for 1961-1990 (historic) and three 30-year time slices in the future. Each dot represents one year. Drought supply threshold is represented by the vertical line, maximum observed demand is shown as the horizontal line (Neilsen 2004, scenario).*

Figure 3.6 illustrates the worst case and least impact scenario changes in annual water supply and crop water demand for Trout Creek of six GCM scenarios, compared with the drought supply threshold of 30 million m^3/a (36% of average annual flow) and observed maximum demand of 10.5 million m^3/a (Neilsen *et al.* 2004). For flows below the drought threshold, local water authorities currently restrict water use. High risk outcomes are defined as years in which water supply is below the drought threshold and water demand above the demand threshold. For all six scenarios, demand is expected to increase and supply is projected to decline. Estimated crop water demand increases most strongly in the HadCM3-A2 scenarios, where by the 2080s, demand exceeds the current observed maximum in every year. For HadCM3-A2, high risk outcomes occur in 1 out of 6 years in the 2050s, and in 1 out of 3 years in the 2080s. High risk outcomes occur more often under A2 than under B2 scenarios due to higher crop water demands in the warmer A2 world.

Table 3.1 illustrates the range of costs of adaptive measures to either decrease in water demand or increase in water supply that are currently available in the region. These costs are expressed by comparison with the least cost option, irrigation scheduling on large holdings, which is equivalent to 0.35 2006-US$/m^3 of supplied water. The most expensive options per unit of water saved or stored are high cost metering and lake pumping to higher elevations. No single option is expected to be sufficient.

Table 3.1: *Relative costs per unit of water saved or supplied in the Okanagan region, British Columbia (adapted from MacNeil 2004).*

Adaptation option	Application	Relative unit cost	Water saved or supplied in % of the current supply
Irrigation scheduling	Large holdings to small holdings	1.0 – 1.7	10%
Public education	Large & medium communities	1.7	10%
Storage	Low to high cost	1.2 – 3.0	Limited (most sites already developed)
Lake pumping	Low (no balancing) to high cost (with balancing)	1.3 – 5.4	0 – 100%
Trickle irrigation	High to medium demand areas	3.0 – 3.3	30%
Leak detection	Average cost	3.1	10 – 15%
Metering	Low to high cost	3.8 – 5.4	20 – 30%

It is a common result of a number of global-scale (Arnell 2004; Alcamo 2002), national-scale (Thomson 2005) and basin-scale assessments (Barnett 2004) that semi-arid and arid basins are the most vulnerable basins on the globe with respect to water stress. If precipitation decreases, irrigation water requirements, which dominate water use in most semi-arid river basins, increase, which adds to the decreases of runoff and streamflow downstream (Eheart 1999), such that irrigation may not be feasible anymore. In the case of the Sacramento-Joaquin River and the Colorado River basins in the Western USA, for example, streamflow changes (as computed by basin-scale hydrological models driven by downscaled GCM NCAR PCM output) are so strong that beyond 2020, not all the present-day water demands (including environmental targets) could be fulfilled any more even with an adapted reservoir management (Barnett 2004). A case study from a semi-arid basin in Canada shows how the balance between water supply and irrigation water demand may be altered due to climate change (Box 3.1), and the costs of this alteration can be assessed. For an aquifer in Texas, net income of farmers is projected to decrease by 16-30% by the 2030s and by 30-45% by the 2090s due to decreased irrigation water supply and increased irrigation water demand, but net total welfare due to water use, which is dominated by municipal and industrial use, decreases by less than 2% (Chen 2001). If freshwater supply has to be replaced by desalinated water due to climate change, then the cost of climate change can be computed from the cost of desalination, which is around US\$ 1/m^3 for seawater and US\$ 0.6/m^3 for brackish water (Zhou 2005), compared to chlorination cost of freshwater of 0.02 US\$/m^3 and costs between 0.35 and 1.9 US\$/m^3 for additional supply in the case study basin in Canada (Box 3.1). In densely populated coastal areas of Bangladesh, China, Egypt, India, and South East Asia (FAO 2003), desalination costs may be prohibitive.

Most semi-arid river basins in developing countries are more vulnerable to climate change than such basins in developed countries, as population and thus water demand in most of these basins is expected to grow rapidly in the future and the coping capacity is low (Millennium Ecosystem Assessment 2005). The latter refers in particular to the rural population without access to reliable water supply from large reservoirs or deep wells. Inhabitants of rural areas are affected directly by changes in the volume and timing of river discharge and groundwater recharge. Thus, even in semi-arid areas where water resources are not overused (low water use-to-availability ratio or high per capita water availability), increased climate variability may have a strong negative impact. In humid river basins, people are likely to cope more easily with the impact of climate change on water demand and availability though they might be less prepared for coping with droughts than people in dry basins (Wilhite 2001).

In global-scale studies of future water stress (or scarcity), water stress is expressed by various indicators, most often long-term average water resources per capita (Arnell 2004) or the water withdrawals to water resources ratio (Alcamo 2005; Alcamo 2003; Vörösmarty 2000). Estimates of the number of people living in areas with high water stress differ significantly among studies. Climate change is but one factor that influences future water stress, while demographic, socio-economic and technological changes may, in most time horizons and regions, play a more important role. In the 2050s, differences in the population development of the four IPCC SRES scenarios are more important for the number of people living in water-stressed river basins (defined as basins with per-capita water resources of less than 1000 m^3/year) than the differences in the emissions scenarios (Arnell 2004). In the A2 scenario, 262-983 million people move into the water-stressed category, and 1092-2761 million people in water-stressed river basins become more stressed, while in the B2 scenario, the ranges are 56-476 million and 670-1538 million, respectively. The ranges are caused by the differing results of the various climate models applied. Without climate change, the number of people living in severely stressed river basins still increases significantly (Table 3.2). If the global number of people living in water-stressed river basins was taken as the indicator of water resources stress, then climate change would appear to reduce water stress. However, increases in runoff mainly occur during high flow seasons, and may not alleviate dry season problems if the extra water is not stored. Notably the basins that apparently benefit from climate change, while limited in number, are in the most populous parts of the world, mainly in east and southeast Asia (Arnell 2004).

Table 3.2: *Number of people living in water stressed river basins with per capita renewable water resources of less than 1000 m^3/yr (Alcamo 2005; Arnell 2004), in million people.*

	Without climate change, (percent of global population) after (Arnell 2004)	*With climate change according to emission scenarios (for several climate model runs)*, after (Arnell 2004)*	*With climate change according to emission scenarios (for several climate model runs)*, after (Alcamo 2005)*
1995	1368 (24%)	1368	1601
A1 2050s	3400 (39%)	2512	
A2 2050s	5590 (48%)	4351-5747	6432-6920
B1 2050s	3400 (39%)	2757	
B2 2050s	3988 (42%)	2766-3958	4909-5166

*The range is due to various climate models and model runs that were used to translate emission scenarios into climate scenarios.

If water stress is not only assessed as a function of population and climate change, but also of changing water use, the importance of non-climatic drivers (here income, water use efficiency, industrial production) even increases (Alcamo 2005). Income growth has a much larger impact than population growth on increasing water use and water stress (as expressed as the water withdrawal-to-water resources ratio). Water stress is modelled to decrease by the 2050s on 20-29% of the global land area (considering two global climate models and the IPCC scenarios A2 and B2) and to increase on 62-76% of the global land area. The principal cause of decreasing water stress is the greater availability of water due to increased precipitation (on 53-83% of the area with decreasing water stress), while the principal cause of increasing water stress is growing water withdrawals (on 87-90% of the area with increasing water stress) and not decreasing precipitation. Growth of domestic water use as stimulated by income growth was found to be dominant (Alcamo 2005).

3.5.2 How will climate change affect flood damages?

Globally, the costs of flood disasters have considerably increased (Munich Re 2005).While there is a wealth of information on the frequency of the hazards and the damages of historic floods and droughts, it is not possible to distinguish the impact of climate change from the impact of demographic and socio-economic changes. Globally, the numbers of great flood disasters have considerably increased (Munich Re 2005).

Using a structural econometric (regression) model of flood damages in the USA based on time series of flood damage, and population, wealth indicator and annual precipitation as predictors, the mean and standard deviation of flood damage is projected to increase by 130% if the mean and standard deviation of annual precipitation increases by 13.5%(Choi 2003). Since consideration of annual precipitation at 344 stations in addition to population and wealth increased the explanatory power from 82% to 89% only, flood losses can be seen as mainly related to increased exposure. This is also supported by a scenario study on the damage due to river and coastal flooding in England and Wales in the 2080s (Hall 2005) where four emissions scenarios where combined with four scenarios of socio-economic change in an SRES-like framework. In all scenarios, the percentage of the population in flood plains that is affected by larger than 75-year floods increases by approx. 50% due to climate change but the total number of people living in the flood plains and the property values vary and thus the flood damages. For the 2°C temperature increase in a B1-type world (by the 2080s), annual damage is estimated to be 5 billion GBP as compared to 1 billion today, while with approximately the same climate change, damage is only 1.5 billion in a B2-type world. In a A1-type world, with a temperature increase of 2° C already by the 2050s, the annual damage would amount to even 15 billion GBP already by the 2050s (and 21 billion GBP by the 2080s) (Hall 2005). The effect of different climate scenarios was explored for one scenario: in the A1-type world, a low rate of climate change (2^{o}C by the 2080s) resulted in estimated average annual flood damages of 15 billion GBP compared with the 21 billion GBP under more rapid climate change (3.9^{o}C by the 2080s) (Evans *et al.* 2004).

The impact of climate change on flood damages can be estimated based on modelled changes in the recurrence interval of current T-year floods and estimates of flood damages of the current floods as determined from stage-discharge relations and detailed property data. With such a methodology, the average annual direct flood damage for three Australian drainage basins was projected to increase by a factor of 4-10 under doubled CO_2 climate conditions (Schreider 2000).

3.6 Adaptation: practices, options and constraints

3.6.1 The context for adaptation

Adaptation to changing conditions in water availability and demand has always been the core of water management, although historically it has concentrated on meeting the increasing demands for water. Except where land-use change occurs, it has conventionally been assumed that the natural resource base is constant. Traditionally, hydrological design rules have been based on the assumption of stationary hydrology, tantamount to the principle that the past is the key to the future, which has a limited validity in the era of global change. As the stationarity assumption is not valid any longer due to climate change, the current procedures for designing water-related infrastructures have to be revised. Otherwise, systems would be over- or under-designed and might either not serve their purpose adequately, or be overly costly.

Changing to meet altered conditions and new ways of managing water are autonomous adaptations which are not deliberately designed to adjust with climate change. On the other hand, planned adaptations take climate change specifically into account.

Integrated water resources management should be an instrument that looks into adaptation measures to climate change, but so far this is in infancy stage. Successful integrated water management strategies include among others: capturing society's views, reshaping planning processes, coordinating land and water resources management, recognizing water quantity and quality linkages, conjunctive use of surface water and groundwater, and protecting and restoring natural system and consideration of climate change. In addition, integrated strategies explicitly address impediments to the flow of information. In the case of large watershed, such as Colorado river basin, these factors cross several time and space scales (Table 3.3).
Lately, some initiatives such as the Dialogue on Water and Climate (DWC) (cf. Box 3.2) have been launched in order to raise awareness of climate change adaptation for the water sector. The main conclusion, out of the DWC initiative, is that the dialogue model provides a important mechanism for developing adaptation strategies with stakeholders. The results of the Dialogues are summarized in (Kabat and van Schaik 2003).

Table 3.3: *Cross-scale issues in the integrated water management of the Colorado River Basin (Pulwarty 2001)*

Temporal	**Issue**
Indeterminate	Flow necessary to protect endangered species
Long-term	Inter-basin allocation and allocation among basin states
Decade	Upper basin delivery obligation
Year	Lake Powell fill obligations to achieve equalization with Lake Mead storage
Seasonal	Peak heating and cooling months
Daily-monthly	Flood control operations
Hourly	Western Area Power Administration's power generation
Spatial Scale	
Global	Climate influences, Grand Canyon National Park
Regional	Prior appropriation (e.g. Upper Colorado River Commission)
State	Different agreements on water marketing within and out of state water district
Municipal and Communities	Watering schedules, treatment, domestic use

Box 3.2: Lessons from the "Dialogue on Water and Climate"

- The aim of the Dialogue on Water and Climate (DWC) was to raise awareness of climate implications for the water sector. The DWC initiated 18 stakeholder dialogues, at the levels of a river basin (Lena, Aral Sea, Yellow River, San Pedro, San Juan, Thukela, Murray-Darling, and Nagoya), a nation (Netherlands and Bangladesh), and a region (Central America, Caribbean Islands, Small Valleys, West Africa, Southern Africa, Mediterranean, South Asia, Southeast Asia, and Pacific Islands), to prepare for actions that reduce vulnerability to climate change. The Dialogues were located in both developed and developing countries and addressed a wide range of vulnerability issues related to water and climate. Participants included water professionals, community representatives, local and national governments, NGOs and researchers.

- The results have been substantive and the strong message going out of these Dialogues to governments, donors and disaster relief agencies is that it is on the ground, in the river basins and in the communities that adaptation actions have to be taken. The Dialogues in Bangladesh and the Small Valleys in Central America have shown that villagers are well aware that climate extremes are becoming more frequent and more intense. The Dialogues also showed that adaptation actions in Bangladesh, the Netherlands, Nagoya, Murray-Darling, and Small Valleys are underway. In other areas, adaptation actions are in the planning stages (Western Africa, Mekong) and others are still in the initial awareness-raising stages (Southern Africa, Aral Sea, Lena Basin).

- The DWC demonstrated that the Dialogue model provides a promising mechanism for developing adaptation strategies with stakeholders.

3.6.2 Adaptation options

IPCC TAR drew a distinction between “supply-side” and “demand-side” adaptation options which are applicable to a range of systems. Table 3.4 summarizes some adaptation options for water resources, designed to ensure supplies during average and drought conditions. .

***Table 3.4**: Some adaptation options for water supply and demand identified in non-Annex I Parties National Communications to the UNFCCC (the list is not exhaustive)*

Supply side	**Demand side**
Prospecting and extraction of groundwater	Improvement of water-use efficiency by recycling water
Increasing storage capacity by building reservoirs and dams	Reduction in water demand for irrigation by adjusting the cropping calendar
Desalination of sea water	Promotion of indigenous practices for sustainable water use
Expansion of rain water storage	Improvement of water management practices

Each option, whether supply-side or demand-side, has a range of advantages and disadvantages, and the relative benefits of different options depend on local circumstances. In general terms, however, supply-side options involving increases to storage capacity or abstraction from water courses tend to have adverse environmental consequences (which can in many cases be alleviated), and the practical effectiveness of many demand-side measures is uncertain, because they often depend on the cumulative actions of individuals. There is also a link between measures to adapt water resources and policies to reduce energy use. Some adaptation options, such as desalination or measures which involve pumping or large volumes of water, use large amounts of energy and may be inconsistent with mitigation policy.

These do not exhaust the range of possibilities. In the Western United States, voluntary water transfers, from agricultural to urban or environmental uses are increasingly being used to accommodate long-term changes in demand (e.g., due to population growth) as well as short-term needs arising from drought emergencies (Miller 2000; Loomis 2003; Brookshire *et al.* 2004; Colby *et al.* 2004). Short-term transfers provide flexibility and increased security for highly valued water uses such as urban supply, and in some circumstances may prove more beneficial than constructing additional storage reservoirs (Goodman 2000). Some major urban water utilities are already incorporating various water market arrangements in their strategic planning for coping with potential effects of climate change. This is true for Metropolitan Water District of Southern California (Metropolitan), which supplies wholesale water to urban water utilities in Los Angeles, Orange, San Diego, Riverside, San Bernardino and Ventura counties. Metropolitan recently concluded a 35-year option contract with Palo Verde Irrigation District. Under the arrangement the district's landowners have agreed not to irrigate up to 29 percent of the valley's farm land at Metropolitan's request, thereby creating a water supply of up to 111,000 acre-feet for Metropolitan. In exchange, landowners receive a one-time payment per acre allocated, and additional annual payments for each acre not irrigated under the program in that year. The contract also provides funding for community improvement programs (Miller and Yates 2006)

Options to counteract an increasing risk of floods can be divided in two categories: either modify the floodwater, for example, via water conveyance system or modify the system's susceptibility to flood damage. In recent years, flood management policy in many countries has shifted from protection towards enhancing society's abilities to live with floods (Kundzewicz & Takeuchi 1999). This may include implementing protection measures, but as part of a package including measures such as enhanced flood forecasting and warning, regulations, zoning, insurance, and relocation. Each measure has advantages and disadvantages, and the choice is site-specific: there is no single one-fits-all measure (Kundzewicz *et al.* 2002).

3.6.3 Limits to adaptation and adaptive capacity

Adaptation in the water sector involves measures to alter hydrological characteristics to suit human demands and measures to alter demands to fit conditions of water availability. It is possible to identify four different types of limits on adaptation to changes in water quantity and quality (Arnell & Delaney 2006). The first is a physical limit: it may not be possible to prevent adverse effects through technical or institutional procedures. For example, it may be impossible to reduce demands for water further without seriously threatening health or livelihoods, it may physically be very difficult to react to the water quality problems associated with higher water temperatures, and in the extreme case it will be impossible to adapt where rivers dry up completely. Second, whilst it may be physically feasible to adapt, there may be economic constraints to what is affordable. Third, there may be political or social limits to the implementation of adaptation measures. In many countries, for example, it is difficult for water supply agencies to construct new reservoirs, and it may be politically very difficult to adapt to reduced reliability of supplies by reducing standards of service. Finally, the capacity of water management agencies may act as a limit on which adaptation measures (if any) can be implemented. The low priority given to water management, lack of coordination between agencies, tensions between national, regional, and local scales, and uncertainty over future climate change impacts constrain the ability of organizations to adapt to changes in water supply and flood risk (Ivey *et al.* 2004; Naess *et al.* 2005). These factors together influence the adaptive capacity of water management system as well as others determinants such as sensitivities to change, internal characteristics of the system (e.g. education and access to knowledge) and external condition such as role of regulation or the market.

Since the TAR there have been a number of studies which have examined explicitly adaptation in real water management systems. Some studies have examined the factors influencing the ability of water management organisations to adapt (Ivey *et al.* 2004; Naess *et al.* 2005; Arnell & Delaney 2006). Others have sought to identify the need for adaptation in specific catchments or water management systems. For example, changes to flow regimes in California would "fundamentally alter California's water rights system" (Hayhoe *et al.* 2004), the changing seasonal distribution of flows across much of the United States would mean that "additional investment may be required"

(Hurd *et al.* 2004), changing streamflow regimes would "pose significant challenges" to the managers of the Columbia River (Mote *et al.* 2003), and an increased frequency of flooding in southern Quebec would mean that "important management decisions will have to be taken" (Roy *et al.* 2001).

A small number of studies have explored the physical feasibility and effectiveness of specific adaptation options. The effectiveness of operational adaptations was explored in the Columbia River basin against a number of criteria (Payne *et al. 200*4). They found that none of the options explored continued to meet all current demands, and that the balance between maintaining power production and maintaining instream flows for fish would have to be renegotiated. In a related study, The effect of different operational adaptations on the performance of the water supply system in the Sacramento-San Joaquin basin, California was examined (Vanrheenen *et al. 200*4). As in the Columbia River, they concluded that "maintaining status quo system performance in the future would not be possible", without changes in demands or expectations. Neither of these studies considered a broad range of adaptation options, including demand management or infrastructure developments.

Comprehensive studies into the feasibility of different adaptation options have been conducted in the Netherlands and the Rhine basin (Tol *et al.* 2003; Middelkoop *et al.* 2004). It was found that the ability to protect physically against flooding depends on geographical context (Tol *et al.* 2003). In some cases it is technically feasible to construct flood embankments; in others high embankments already exist or geotechnical conditions make physical protection difficult. Radical flood management measures – such as the creation of a new flood overflow route for the River Rhine, able to reduce the physical flood risk to the Rhine delta in the Netherlands, would be extremely difficult politically to implement (Tol *et al.* 2003).

3.6.4 Uncertainty and risk: decision-making under uncertainty

Climate change poses two major conceptual challenges to water managers. First, it means that it is no longer appropriate to assume that past hydrological conditions will continue into the future (the traditional assumption), and, second, that the future is highly uncertain. These together are likely to lead to changes in the procedures used to manage water resources and water-related hazards. This sub-section covers three issues: developments in the conceptual understanding of sources of uncertainty and how to characterise them, examples of how water managers in practice are making climate change decisions under uncertainty, and an assessment of different ways of managing resources under uncertainty.

The vast majority of published water resources impact assessments have used just a small number of scenarios. These have demonstrated that impacts vary between scenarios, although temperature-based impacts, such as changing in the timing of streamflows, tend to be more robust (Maurer & Duffy 2005), and the use of a scenario-based approach to water management in the face of climate change is therefore widely recommended (Beuhler (2003), Simonovic & Li (2003)). There are, however, two problems. First, the large range for different climate model-based scenarios suggests that adaptive planning should not be based on only a few scenarios (Prudhomme *et al.* 2003): there is no guarantee that the range simulated represents the full range. Second, it is difficult to evaluate the credibility of individual scenarios. By making assumptions about the probability distributions of the different drivers of climate change, however, it is possible to construct probability distributions of hydrological outcomes, although the resulting probability distributions will be influenced by the assumed initial probability distributions. Jones & Page (2001) constructed probability distributions for water storage, environmental flows and irrigation allocations in the Macquarie River catchment, Australia, showing that the estimated distributions were in fact little affected by assumptions about probability distributions of drivers of change.

Water managers in a few countries, including the Netherlands, Australia, UK, and USA have begun to consider the implications of climate change explicitly in flood and water supply management. In the UK, for example, design flood magnitudes can be increased by 20% to reflect the possible effects of climate change (Richardson 2002), the figure of 20% was based on early impact assessments), and methods are under review following the publication of new scenarios (Hawkes *et al.* 2003). Water supply companies in England and Wales used four climate scenarios in their 2004 review of future resource requirements, using a formalised procedure developed by the environmental and economic regulators (Arnell & Delaney 2006). This procedure basically involved the companies estimating when climate change might impact upon reliability of supply, and undertaking different actions depending on when these impacts would be felt (in most cases estimated effects were too far into the future to cause any changes in practice now, but in some instances the impacts would be soon enough to necessitate undertaking more detailed investigations now). Dessai *et al.* (2005) describe an example where water supply managers in Australia were given information on the likelihood of drought conditions continuing, under different assumptions about the magnitude of climate change. They used this information to decide on whether to invoke contingency plans to add temporary supplies or tighten restrictions on water use.

A rather different way of coping with the uncertainty associated with estimates of future climate change on hydrological and water resources characteristics is to adopt management measures which are robust to uncertainty. Integrated water resources management, for example, is based around the concepts of flexibility and adaptability, using measures which can be easily altered or are robust to changing conditions. These tools, including water conservation, reclamation, conjunctive use of surface and groundwater and desalination of brackish water, have been advocated as a means of reacting to climate change threats to water supply in California (e.g. Beuhler 2003). Similarly, resilient strategies for flood management, such as allowing rivers to temporarily flood and reducing exposure to flood damage, are preferable to traditional “resistance” (protection) strategies in the face of uncertainty (Klijn *et al.* 2004).

3.7 Conclusions: Implications for sustainable development

A temperature rise of only 1°C since pre-industrial times, which is only a further 0.4°C above today’s increase, would cause additional climate impacts. For the 2020s the additional number of people in water shortage is estimated to be in the range 400-800 million (Parry *et al.* 2001; Martinez-Villalbe and Pinol 2002). Most of the seven Millennium Development Goals (MDGs) are related directly or indirectly to water management and climate change. Some main concerns are presented in Table 3.5 (UNDP 2006).

Table 3.5: *Potential contribution of the water sector to attain the MDGs*

Goals	*Direct relation to water*	*Indirect relation to water*
Goal 1: Erradicate extreme poverty and hunger	Water as factor in many production activities (e.g. agriculture, animal husbandry, cottage industry) Sustainable production of fish, tree crops and other food brought together in common property resources	Reduced ecosystem degradation makes better local-level sustainable development Reduced urban hunger by cheaper food from more reliable water supplies
Goal 2: Achieve universal		Improved school attendance from improved health and reduced water

education		carrying burdens, especially for girls
Goal 3: Promote gender equity and empower women	Development of gender-sensitive water management programmes	Reduced time waste and health burdens from improved water service lead to more time for income earning and more balanced gender roles
Goal 4: Reduce child mortality	Improved access to drinking water of more adequate quantity and quality and sanitation reduced the main factors of morbidity and mortality of young children	
Goal 6: Combat HIV/AIDS, malaria and other diseases	Improved access to water and sanitation support HIV/AIDS affected households and may improve the impact of health care programmes Better water management reduces mosquito habitats and the risk of malaria transmission	
Goal 7: Ensure environmental sustainability	Improved water management reduces water consumption and recycle nutrients and organics Actions to ensure access to improved and, possibly, productive eco-sanitation for poor households Actions to improve water supply and sanitation services for poor human communities Actions to reduce wastewater discharge and improve environmental health in slum areas	Develop operation, maintenance, and cost recovery system to ensure sustainability of service delivery

In many regions of the globe, these climate change impacts may affect sustainable development and put at risk the reduction of poverty. Even with optimal water management, it would not be possible to avoid negative impacts. Fig. 3.7 shows some key cases around the world, where freshwater-related climate change impacts are threat to the sustainable development of the affected regions,

The precise interpretation of "sustainable" water resources management varies considerably among different studies. All definitions broadly include the concept of maintaining and enhancing the environment, but interpretations of the "environment" vary. Franks *et al.*, (2004) refer to the need to protect and enhance the water environment, taking into account competing users, instream ecosystems and wetlands. Other authors consider the wider environmental implications of water management policies, such as implications for land management, or the implications of land management policies for the water environment (Carter *et al.* 2005).

Since 2000, decision-support tools have been proposed to aid the sustainable management of water resources (e.g. Zacharias *et al.* 2003; Ochola *et al.* 2004; Guo *et al.* 2004; Fassio *et al.* 2005). However, few studies have explicitly incorporated the issue of climate change (Kashyap 2004).

Energy, equity and water governance are key issues when linking climate change and sustainable development. Few studies have taken into account the carbon footprint of the water sector. For example, desalination has been proposed as a sustainable water management measure (Boutkan & Stikker 2004), even though it uses large amounts of energy. Many water management actions and adaptations, particularly those involving pumping or treating water, are very energy-intensive. Their implementation would affect energy emissions, and energy policy could affect their implementation (Mata & Budhooram 2004).

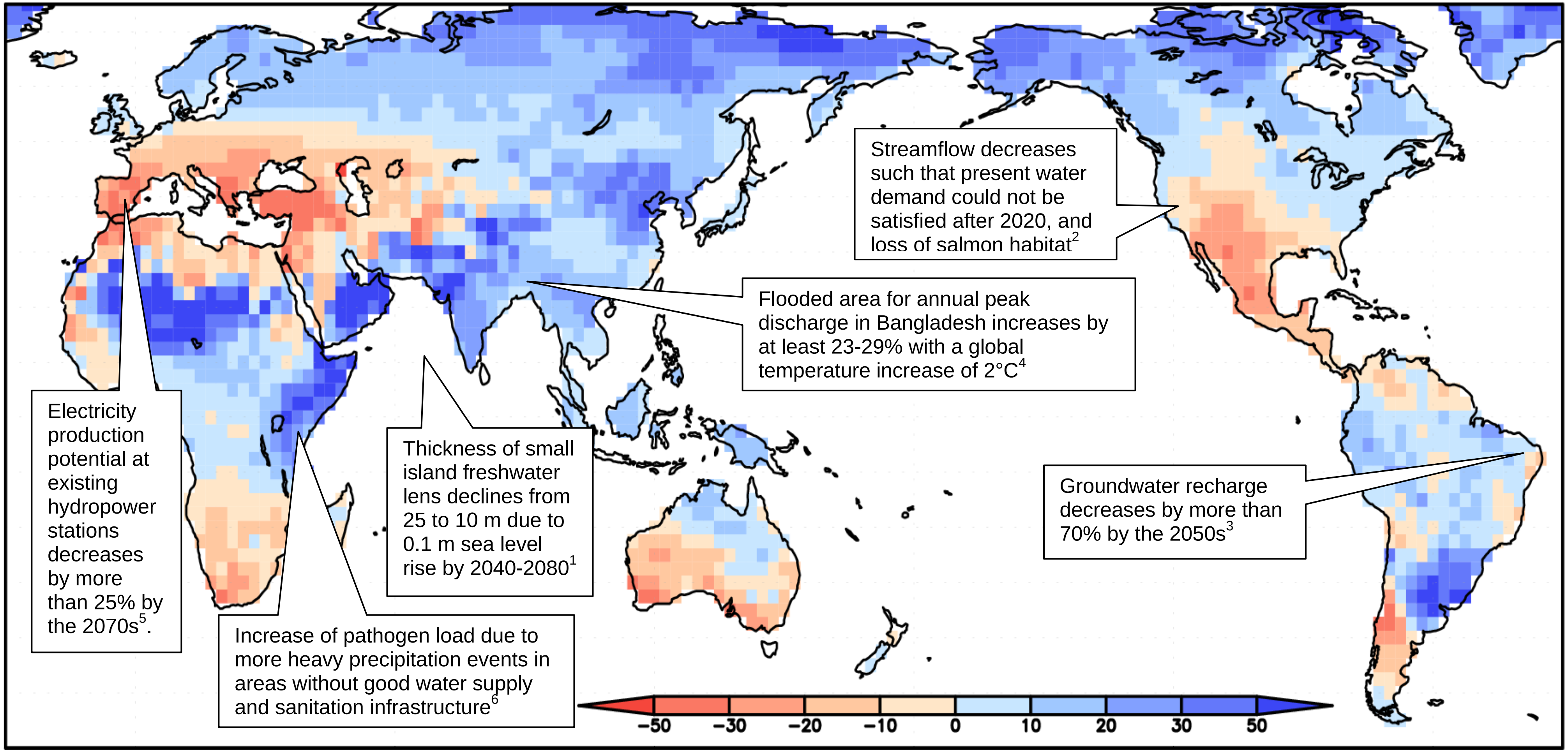


***Figure 3.7**: Illustrative map of future climate change impacts on freshwater which are a threat to the sustainable development of the affected regions. 1: (Bobba 2000), 2: (Barnett 2004, environmental), 3: (Döll 2005), 4 (Mirza et al. 2003) 5: (Lehner 2005) 6: (Kistemann 2002). Background map: Ensemble mean change of annual mean runoff between present (1981-2000) and 2100 (Nohara et al. 2006) blue: increase, red: decrease. Please note that increase of pathogen load of surface waters due to increased heavy precipitation and runoff events will be a threat in almost all developed regions of the world but no quantitative assessments of this climate change impacts are available.*

Equity in impact of an adaptation action is a key aspect of sustainability and effectiveness of adaptation (Adger *et al.* 2005). Examples of potential inequities occur where people benefit differently from an adaptation option (such as publicly-funded flood protection) or where people are displaced or otherwise adversely impacted in order to implement an adaptation option (e.g. building a new reservoir).

Water governance has been suggested as an important component of managing water in order to achieve sustainable water resources, for a range of political, socio-economic and administrative systems (GWP 2002; World Water Assessment Programme 2003; Eakin and Lemos 2006). Mitigation measures which reduce greenhouse emissions cut the impacts of climate change on water resources, but do not eliminate impacts. The impact of climate change in the future water resources depends on the future state of the world. The number of people exposed to water shortage and potentially affected is scenario dependent. For example, stabilization at 550 ppmv (resulting in increase in temperature since pre-industrial times below the 2 °C target) only reduces the number of people adversely affected by climate change by 30-50% (Arnell 2006)
Finally, it is important to mention that climate change is the most important and geographically extensive physical driver that stimulates changes in access to water and the future availability of water supplies. This brings important consequences for sustainable development.

3.8 Key uncertainties and research priorities

There are major uncertainties in quantitative projections of changes in hydrological characteristics for a drainage basin, the basic unit of water management. Precipitation, the principal input signal to water systems is not reliably simulated in present climate models, so the projections are highly uncertain and strongly model-dependent. This has two implications. First, adaptation procedures need to be developed, which do not rely on precise projections of changes in river discharge, groundwater, etc. Second, based on the studies done so far, it is difficult to assess, in a reliable way, water-related consequences of climate policies and emission pathways. Research on methods of adaptation in the face of these uncertainties is needed. Whereas it is difficult to make concrete projections; it is known that hydrological characteristics will change in the future. Water managers in some countries (e.g. flood management and water supply management in the UK) are already considering explicitly how to incorporate the potential effects of climate change into policies and specific designs.

Research needs into water-climate interface can be seen in two broader categories:

- to improve understanding and estimation, in quantitative terms, of climate change impacts on freshwater resources and their management;
- to fulfil pragmatic information needs of water managers who are responsible for adaptation.

Progress in research depends on improvement in data availability, calling for enhancement of monitoring endeavours worldwide, addressing the challenges posed by projected climate change to freshwater resources and reversing the tendency of shrinking observation networks. Broadening access to available observation data is a pre-requisite condition to improve understanding of the ongoing changes. Relatively short hydrometric records can underplay the full extent of natural variability and confound detection studies, while long-term river flow reconstruction can place recent trends and extremes in a broader context.

There is a scale mismatch between the large-scale climatic models and the catchment scale, which needs to be resolved. Water is managed at the catchment scale and adaptation is local, while global climate models work on large spatial grids. Increasing resolution of adequately validated, regional climate models and statistical downscaling would produce information of more relevance to water management.

Among the research issues related to climate-water interface, where developments are needed, are the following:

- It is necessary to improve understanding of sources of uncertainty in order to improve credibility of projections, which are strongly scenario- and model-dependent. Scenarios, which represent unpredictable details of socio-economic futures, have themselves strong inherent uncertainty.
- Impacts of change in climate variability need to be integrated into the impact modeling efforts. For instance, improvements in coupling of climate models with the land-use change including vegetation change and anthropogenic activity such as irrigation are necessary.
- Climate change impacts on water quality are poorly understood. There is a strong need for enhancing research into this area, with particular reference to impact of extreme events and covering the needs of both developed and developing countries.
- Relatively few results are available on costing of climate change impacts and adaptation options related to water resources, which is of extreme practical importance.
- Research into human-dimension indicators of climate change impacts is in its infancy phase and a vigorous growth is necessary.
- Impacts of climate change on aquatic ecosystems (not only temperatures, but also altered flow regimes, water levels, and ice cover) are not adequately understood.
- Detection and attribution of changes in freshwater resources, with particular reference to characteristics of extremes is a challenging research priority.
- There are challenges and opportunities posed by the advent of probabilistic climate change scenarios for water resource management (Wilby and Harris 2006, scenarios).
- Despite its significance, groundwater has received little attention for climate change impact assessment compared with surface water resources.
- Water resources management clearly impacts on many other policy areas (e.g. nature conservation). Hence there is an opportunity to align adaptation measures across different sectors (Holman *et al.* 2005a, b). What additional tools and techniques are still required to facilitate adaptation options appraisal across multiple water-dependent sectors?

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