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Freshwater resources and their management

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

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Executive summary

The impacts of climate change on freshwater systems and their management are mainly due to the observed and projected increases in temperature, sea level and precipitation variability (very high confidence).
More than one-sixth of the world's population live in glacier- or snowmelt-fed river basins and will be affected by the seasonal shift in streamflow, an increase in the ratio of winter to annual flows, and possibly the reduction in low flows caused by decreased glacier extent or snow water storage (high confidence) [3.4.1, 3.4.3]. Sea-level rise will extend areas of salinisation of groundwater and estuaries, resulting in a decrease in freshwater availability for humans and ecosystems in coastal areas (very high confidence) [3.2, 3.4.2]. Increased precipitation intensity and variability is projected to increase the risks of flooding and drought in many areas (high confidence) [3.3.1].

Semi-arid and arid areas are particularly exposed to the impacts of climate change on freshwater (high confidence).
Many of these areas (e.g., Mediterranean basin, western USA, southern Africa, and north-eastern Brazil) will suffer a decrease in water resources due to climate change (very high confidence) [3.4, 3.7]. Efforts to offset declining surface water availability due to increasing precipitation variability will be hampered by the fact that groundwater recharge will decrease considerably in some already water-stressed regions (high confidence) [3.2, 3.4.2], where vulnerability is often exacerbated by the rapid increase in population and water demand (very high confidence) [3.5.1].

Higher water temperatures, increased precipitation intensity, and longer periods of low flows exacerbate many forms of water pollution, with impacts on ecosystems, human health, water system reliability and operating costs (high confidence).
These pollutants include sediments, nutrients, dissolved organic carbon, pathogens, pesticides, salt, and thermal pollution [3.2, 3.4.4, 3.4.5].

Climate change affects the function and operation of existing water infrastructure as well as water management practices (very high confidence).
Adverse effects of climate on freshwater systems aggravate the impacts of other stresses, such as population growth, changing economic activity, land-use change, and urbanisation (very high confidence) [3.3.2, 3.5]. Globally, water demand will grow in the coming decades, primarily due to population growth and increased affluence; regionally, large changes in irrigation water demand as a result of climate change are likely (high confidence) [3.5.1]. Current water management practices are very likely to be inadequate to reduce the negative impacts of climate change on water supply reliability, flood risk, health, energy, and aquatic ecosystems (very high confidence) [3.4, 3.5]. Improved incorporation of current climate variability into water-related management would make adaptation to future climate change easier (very high confidence) [3.6].

Adaptation procedures and risk management practices for the water sector are being developed in some countries and regions (e.g., Caribbean, Canada, Australia, Netherlands, UK, USA, Germany) that have recognised projected hydrological changes with related uncertainties (very high confidence).
Since the IPCC Third Assessment, uncertainties have been evaluated, their interpretation has improved, and new methods (e.g., ensemble-based approaches) are being developed for their characterisation (very high confidence) [3.4, 3.5]. Nevertheless, quantitative projections of changes in precipitation, river flows, and water levels at the river-basin scale remain uncertain (very high confidence) [3.3.1, 3.4].

The negative impacts of climate change on freshwater systems outweigh its benefits (high confidence).
All IPCC regions (see Chapters 3–16) show an overall net negative impact of climate change on water resources and freshwater ecosystems (high confidence). Areas in which runoff is projected to decline are likely to face a reduction in the value of the services provided by water resources (very high confidence) [3.4, 3.5]. The beneficial impacts of increased annual runoff in other areas will be tempered by the negative effects of increased precipitation variability and seasonal runoff shifts on water supply, water quality, and flood risks (high confidence) [3.4, 3.5].

3.1 Introduction

Water is indispensable for all forms of life. It is needed in almost all human activities. Access to safe freshwater is now regarded as a universal human right (United Nations Committee on Economic, Social and Cultural Rights, 2003), and the Millennium Development Goals include the extended access to safe drinking water and sanitation (UNDP, 2006). Sustainable management of freshwater resources has gained importance at regional (e.g., European Union, 2000) and global scales (United Nations, 2002, 2006; World Water Council, 2006), and 'Integrated Water Resources Management' has become the corresponding scientific paradigm.

Figure 3.1 shows schematically how human activities affect freshwater resources (both quantity and quality) and their management. Anthropogenic climate change is only one of many pressures on freshwater systems. Climate and freshwater systems are interconnected in complex ways. Any change in one

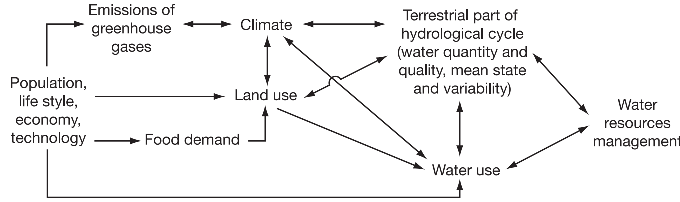

Figure 3.1. *Impact of human activities on freshwater resources and their management, with climate change being only one of multiple pressures (modified after Oki, 2005).*

of these systems induces a change in the other. For example, the draining of large wetlands may cause changes in moisture recycling and a decrease of precipitation in particular months, when local boundary conditions dominate over the large-scale circulation (Kanae et al., 2001). Conversely, climate change affects freshwater quantity and quality with respect to both mean states and variability (e.g., water availability as well as floods and droughts). Water use is impacted by climate change, and also, more importantly, by changes in population, lifestyle, economy, and technology; in particular by food demand, which drives irrigated agriculture, globally the largest water-use sector. Significant changes in water use or the hydrological cycle (affecting water supply and floods) require adaptation in the management of water resources.

In the Working Group II Third Assessment Report (TAR; IPCC, 2001), the state of knowledge of climate change impacts on hydrology and water resources was presented in the light of literature up to the year 2000 (Arnell et al., 2001). These findings are summarised 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, with lower flows in summer and autumn.
- Glacier retreat is likely to continue, and many small glaciers may disappear.
- Generally, water quality is likely to be degraded by higher water temperatures.
- Flood magnitude and frequency are likely to increase in most regions, and volumes of low flows are likely to decrease in many regions.
- Globally, demand for water is increasing as a result of population growth and economic development, but is falling in some countries, due to greater water-use efficiency.
- The impact of climate change on water resources also depends on system characteristics, changing pressures on the system, how the management of the system evolves, and what adaptations to climate change are implemented.
- Unmanaged systems are likely to be most vulnerable to climate change.
- Climate change challenges existing water resource management practices by causing trends not previously experienced and adding new uncertainty.
- Adaptive capacity is distributed very unevenly across the world.

These findings have been confirmed by the current assessment. Some of them are further developed, and new findings have been added. This chapter gives an overview of the future impacts of climate change on freshwater resources and their management, mainly based on research published after the Third Assessment Report. Socio-economic aspects, adaptation issues, implications for sustainable development, as well as uncertainties and research priorities, are also covered. The focus is on terrestrial water in liquid form, due to its importance for freshwater management. Various aspects of climate change impacts on water resources and related vulnerabilities are presented (Section 3.4) as well as the impacts on water-use sectors (Section 3.5). Please refer to Chapter 1 for further information on observed trends, to Chapter 15 (Sections 15.3 and 15.4.1) for freshwater in cold regions and to Chapter 10 of the Working Group I Fourth Assessment Report (Meehl et al., 2007) - Section 10.3.3 for the cryosphere, and Section 10.3.2.3 for impacts on precipitation, evapotranspiration and soil moisture. While the impacts of increased water temperatures on aquatic ecosystems are discussed in this volume in Chapter 4 (Section 4.4.8), findings with respect to the effect of changed flow conditions on aquatic ecosystems are presented here in Section 3.5. The health effects of changes in water quality and quantity are covered in Chapter 8, while regional vulnerabilities related to freshwater are discussed in Chapters 9–16.

3.2 Current sensitivity/vulnerability

With higher temperatures, the water-holding capacity of the atmosphere and evaporation into the atmosphere increase, and this favours increased climate variability, with more intense precipitation and more droughts (Trenberth et al., 2003). The hydrological cycle accelerates (Huntington, 2006). While temperatures are expected to increase everywhere over land and during all seasons of the year, although by different increments, precipitation is expected to increase globally and in many river basins, but to decrease in many others. In addition, as shown in the Working Group I Fourth Assessment Report, Chapter 10, Section 10.3.2.3 (Meehl et al., 2007), precipitation may increase in one season and decrease in another. These climatic changes lead to changes in all components of the global freshwater system.

Climate-related trends of some components during the last decades have already been observed (see Table 3.1). For a number of components, for example groundwater, the lack of data makes it impossible to determine whether their state has changed in the recent past due to climate change. During recent decades, non-climatic drivers (Figure 3.1) have exerted strong pressure on freshwater systems. This has resulted in water pollution, damming of rivers, wetland drainage, reduction in streamflow, and lowering of the groundwater table (mainly due to irrigation). In comparison, climate-related changes have been small, although this is likely to be different in the future as the climate change signal becomes more evident.

Current vulnerabilities to climate are strongly correlated with climate variability, in particular precipitation variability. These vulnerabilities are largest in semi-arid and arid low-income countries, where precipitation and streamflow are concentrated over a few months, and where year-to-year variations are high (Lenton, 2004). In such regions a lack of deep groundwater wells or reservoirs (i.e., storage) leads to a high level of vulnerability to climate variability, and to the climate changes that are likely to further increase climate variability in future. In addition, river basins that are stressed due to non-climatic drivers are likely to be vulnerable to climate change. However, vulnerability to climate change exists everywhere, as water infrastructure (e.g., dikes and pipelines) has been designed for stationary climatic conditions, and water resources management has only just started to take into

Table 3.1. *Climate-related observed trends of various components of the global freshwater system. Reference is given to Chapters 1 and 15 of this volume and to the Working Group I Fourth Assessment Report (WGI AR4) Chapter 3 (Trenberth et al., 2007) and Chapter 4 (Lemke et al., 2007).*

	Observed climate-related trends
Precipitation	Increasing over land north of 30°N over the period 1901–2005. Decreasing over land between 10°S and 30°N after the 1970s (WGI AR4, Chapter 3, Executive summary). Increasing intensity of precipitation (WGI AR4, Chapter 3, Executive summary).
Cryosphere	
Snow cover	Decreasing in most regions, especially in spring (WGI AR4, Chapter 4, Executive summary).
Glaciers	Decreasing almost everywhere (WGI AR4, Chapter 4, Section 4.5).
Permafrost	Thawing between 0.02 m/yr (Alaska) and 0.4 m/yr (Tibetan Plateau) (WGI AR4 Chapter 4 Executive summary; this report, Chapter 15, Section 15.2).
Surface waters	
Streamflow	Increasing in Eurasian Arctic, significant increases or decreases in some river basins (this report, Chapter 1, Section 1.3.2). Earlier spring peak flows and increased winter base flows in Northern America and Eurasia (this report, Chapter 1, Section 1.3.2).
Evapotranspiration	Increased actual evapotranspiration in some areas (WGI AR4, Chapter 3, Section 3.3.3).
Lakes	Warming, significant increases or decreases of some lake levels, and reduction in ice cover (this report, Chapter 1, Section 1.3.2).
Groundwater	No evidence for ubiquitous climate-related trend (this report, Chapter 1, Section 1.3.2).
Floods and droughts	
Floods	No evidence for climate-related trend (this report, Chapter 1, Section 1.3.2), but flood damages are increasing (this section).
Droughts	Intensified droughts in some drier regions since the 1970s (this report, Chapter 1, Section 1.3.2; WGI AR4, Chapter 3, Executive summary).
Water quality	No evidence for climate-related trend (this report, Chapter 1, Section 1.3.2).
Erosion and sediment transport	No evidence for climate-related trend (this section).
Irrigation water demand	No evidence for climate-related trend (this section).

account the uncertainties related to climate change (see Section 3.6). In the following paragraphs, the current sensitivities of components of the global freshwater system are discussed, and example regions, whose vulnerabilities are likely to be exacerbated by climate change, are highlighted (Figure 3.2).

Surface waters and runoff generation

Changes in river flows as well as lake and wetland levels due to climate change depend on changes in the volume, timing and intensity of precipitation (Chiew, 2007), snowmelt and whether precipitation falls as snow or rain. Changes in temperature, radiation, atmospheric humidity, and wind speed affect potential evapotranspiration, and this can offset small increases in precipitation and exaggerate further the effect of decreased precipitation on surface waters. In addition, increased atmospheric CO_2 concentration directly alters plant physiology, thus affecting evapotranspiration. Many experimental (e.g., Triggs et al., 2004) and global modelling studies (e.g., Leipprand and Gerten, 2006; Betts et al., 2007) show reduced evapotranspiration, with only part of this reduction being offset by increased plant growth due to increased CO_2 concentrations. Gedney et al. (2006) attributed an observed 3% rise in global river discharges over the 20th century to CO_2-induced reductions in plant evapotranspiration (by 5%) which were offset by climate change (which by itself would have decreased discharges by 2%). However, this attribution is highly uncertain, among other reasons due to the high uncertainty of observed precipitation time series.

Different catchments respond differently to the same change in climate drivers, depending largely on catchment physiogeographical and hydrogeological characteristics and the amount of lake or groundwater storage in the catchment.

A number of lakes worldwide have decreased in size during the last decades, mainly due to human water use. For some, declining precipitation was also a significant cause; e.g., in the case of Lake Chad, where both decreased precipitation and increased human water use account for the observed decrease in lake area since the 1960s (Coe and Foley, 2001). For the many lakes, rivers and wetlands that have shrunk mainly due to human water use and drainage, with negative impacts on ecosystems, climate change is likely to exacerbate the situation if it results in reduced net water availability (precipitation minus evapotranspiration).

Groundwater

Groundwater systems generally respond more slowly to climate change than surface water systems. Groundwater levels correlate more strongly with precipitation than with temperature, but temperature becomes more important for shallow aquifers and in warm periods.

Floods and droughts

Disaster losses, mostly weather- and water-related, have grown much more rapidly than population or economic growth, suggesting a negative impact of climate change (Mills, 2005). However, there is no clear evidence for a climate-related trend in floods during the last decades (Table 3.1; Kundzewicz et al., 2005; Schiermeier, 2006). However, the observed increase in precipitation intensity (Table 3.1) and other observed climate changes, e.g., an increase in westerly weather patterns during winter over Europe, leading to very rainy low-pressure systems that often trigger floods (Kron and Bertz, 2007), indicate that climate might already have had an impact on floods. Globally,

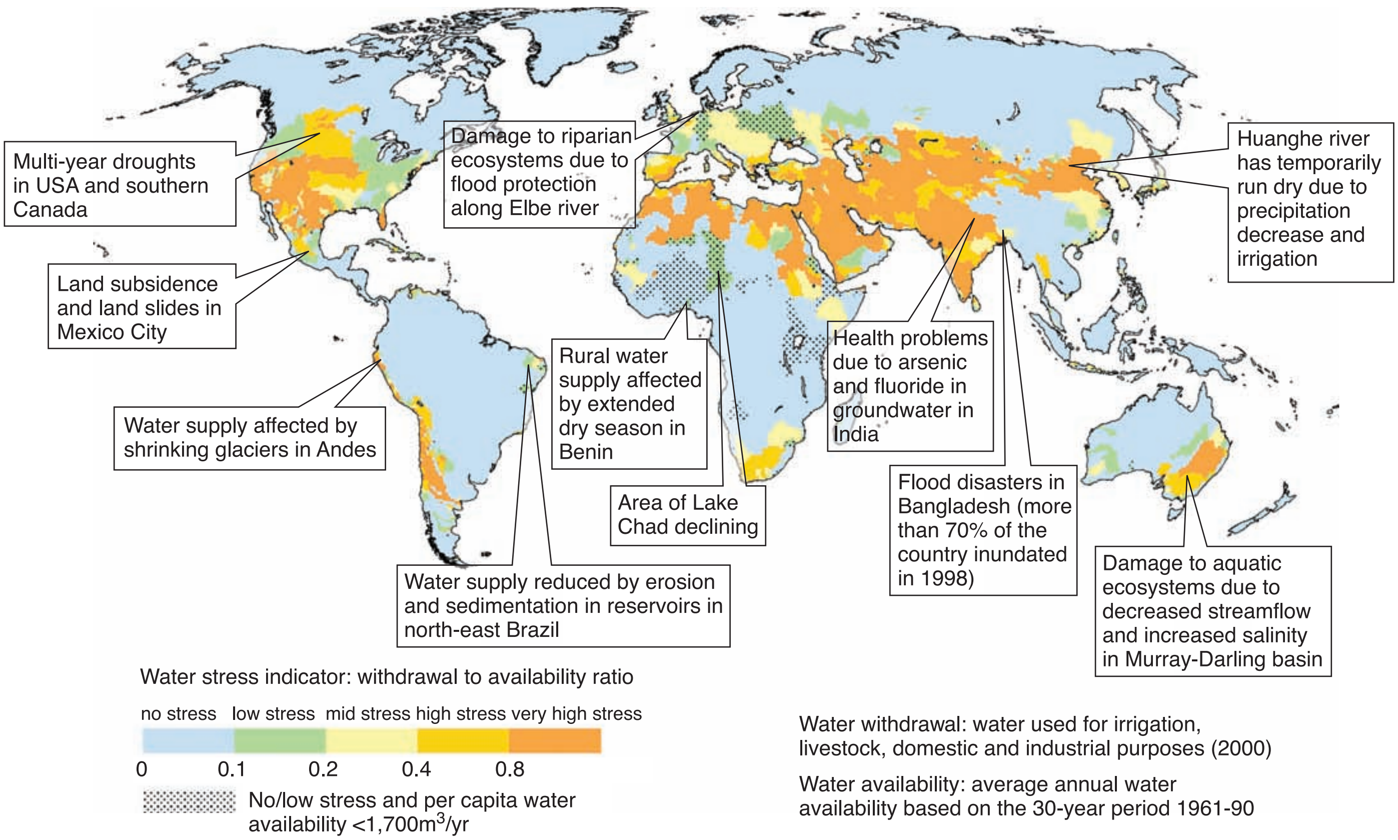

Figure 3.2. *Examples of current vulnerabilities of freshwater resources and their management; in the background, a water stress map based on Alcamo et al. (2003a). See text for relation to climate change.*

the number of great inland flood catastrophes during the last 10 years (between 1996 and 2005) is twice as large, per decade, as between 1950 and 1980, while economic losses have increased by a factor of five (Kron and Bertz, 2007). The dominant drivers of the upward trend in flood damage are socio-economic factors, such as increased population and wealth 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/yr on average) than all other natural disasters (WDR, 2003, 2004). In Bangladesh, three extreme floods have occurred in the last two decades, and in 1998 about 70% of the country's area was inundated (Mirza, 2003; Clarke and King, 2004). In some river basins, e.g., the Elbe river basin in Germany, increasing flood risk drives the strengthening of flood protection systems by structural means, with detrimental effects on riparian and aquatic ecosystems (Wechsung et al., 2005).

Droughts affect rain-fed agricultural production as well as water supply for domestic, industrial, and agricultural purposes. Some semi-arid and sub-humid regions of the globe, e.g., Australia (see Chapter 11, Section 11.2.1), western USA and southern Canada (see Chapter 14, Section 14.2.1), and the Sahel (Nicholson, 2005), have suffered from more intense and multi-annual droughts, highlighting the vulnerability of these regions to the increased drought occurrence that is expected in the future due to climate change.

Water quality

In lakes and reservoirs, climate change effects are mainly due to water temperature variations, which result directly from climate change or indirectly through an increase in thermal pollution as a result of higher demands for cooling water in the energy sector. This affects oxygen regimes, redox potentials,[1] lake stratification, mixing rates, and biota development, as they all depend on temperature (see Chapter 4). Increasing water temperature affects the self-purification capacity of rivers by reducing the amount of oxygen that can be dissolved and used for biodegradation. A trend has been detected in water temperature in the Fraser River in British Columbia, Canada, for longer river sections reaching a temperature over 20°C, which is considered the threshold beyond which salmon habitats are degraded (Morrison et al., 2002). Furthermore, increases in intense rainfall result in more nutrients, pathogens, and toxins being washed into water bodies. Chang et al. (2001) reported increased nitrogen loads from rivers of up to 50% in the Chesapeake and Delaware Bay regions due to enhanced precipitation.

Numerous diseases linked to climate variations can be transmitted via water, either by drinking it or by consuming crops irrigated with polluted water (Chapter 8, Section 8.2.5). The presence of pathogens in water supplies has been related to extreme rainfall events (Yarze and Chase, 2000; Curriero et al., 2001; Fayer et al., 2002; Cox et al., 2003; Hunter, 2003). In aquifers, a possible relation between virus content and extreme

[1] A change in the redox potential of the environment will mean a change in the reactions taking place in it, moving, for example, from an oxidising (aerobic) to a reducing (anaerobic) system.

rainfall has been identified (Hunter, 2003). In the USA, 20 to 40% of water-borne disease outbreaks can be related to extreme precipitation (Rose et al., 2000). Effects of dry periods on water quality have not been adequately studied (Takahashi et al., 2001), although lower water availability clearly reduces dilution.

At the global scale, health problems due to arsenic and fluoride in groundwater are more important than those due to other chemicals (United Nations, 2006). Affected regions include India, Bangladesh, China, North Africa, Mexico, and Argentina, with more than 100 million people suffering from arsenic poisoning and fluorosis (a disease of the teeth or bones caused by excessive consumption of fluoride) (United Nations, 2003; Clarke and King, 2004; see also Chapter 13, Section 13.2.3).

One-quarter of the global population lives in coastal regions; these are water-scarce (less than 10% of the global renewable water supply) (Small and Nicholls, 2003; Millennium Ecosystem Assessment, 2005b) and are undergoing rapid population growth. Saline intrusion due to excessive water withdrawals from aquifers is expected to be exacerbated by the effect of sea-level rise, leading to even higher salinisation and reduction of freshwater availability (Klein and Nicholls, 1999; Sherif and Singh, 1999; Essink, 2001; Peirson et al., 2001; Beach, 2002; Beuhler, 2003). Salinisation affects estuaries and rivers (Knighton et al., 1992; Mulrennan and Woodroffe, 1998; Burkett et al., 2002; see also Chapter 13). Groundwater salinisation caused by a reduction in groundwater recharge is also observed in inland aquifers, e.g., in Manitoba, Canada (Chen et al., 2004).

Water quality problems and their effects are different in type and magnitude in developed and developing countries, particularly those stemming from microbial and pathogen content (Lipp et al., 2001; Jiménez, 2003). In developed countries, flood-related water-borne diseases are usually 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, with the exception of cholera and salmonella, studies of the relationship between climate change and micro-organism content in water and wastewater do not focus on pathogens of interest in developing countries, such as specific protozoa or parasitic worms (Yarze and Chase, 2000; Rose et al., 2000; Fayer et al., 2002; Cox et al., 2003; Scott et al., 2004). One-third of urban water supplies in Africa, Latin America and the Caribbean, and more than half in Asia, are operating intermittently during periods of drought (WHO/UNICEF, 2000). This adversely affects water quality in the supply system.

Erosion and sediment transport

Rainfall amounts and intensities are the most important factors controlling climate change impacts on water erosion (Nearing et al., 2005), and they affect many geomorphologic processes, including slope stability, channel change, and sediment transport (Rumsby and Macklin, 1994; Rosso et al., 2006). There is no evidence for a climate-related trend in erosion and sediment transport in the past, as data are poor and climate is not the only driver of erosion and sediment transport. Examples of vulnerable areas can be found in north-eastern Brazil, where the sedimentation of reservoirs is significantly decreasing water storage and thus water supply (De Araujo et al., 2006); increased erosion due to increased precipitation intensities would exacerbate this problem. Human settlements on steep hill slopes, in particular informal settlements in metropolitan areas of developing countries (United Nations, 2006), are vulnerable to increased water erosion and landslides.

Water use, availability and stress

Human water use is dominated by irrigation, which accounts for almost 70% of global water withdrawals and for more than 90% of global consumptive water use, i.e., the water volume that is not available for reuse downstream (Shiklomanov and Rodda, 2003). In most countries of the world, except in a few industrialised nations, water use has increased over the last decades due to demographic and economic growth, changes in lifestyle, and expanded water supply systems. Water use, in particular irrigation water use, generally increases with temperature and decreases with precipitation. There is no evidence for a climate-related trend in water use in the past. This is due to the fact that water use is mainly driven by non-climatic factors and to the poor quality of water-use data in general and time series in particular.

Water availability from surface sources or shallow groundwater wells depends on the seasonality and interannual variability of streamflow, and safe water supply is determined by seasonal low flows. In snow-dominated basins, higher temperatures lead to reduced streamflow and thus decreased water supply in summer (Barnett et al., 2005), for example in South American river basins along the Andes, where glaciers are shrinking (Coudrain et al., 2005). In semi-arid areas, climate change may extend the dry season of no or very low flows, which particularly affects water users unable to rely on reservoirs or deep groundwater wells (Giertz et al., 2006)

Currently, human beings and natural ecosystems in many river basins suffer from a lack of water. In global-scale assessments, basins with water stress are defined either as having a per capita water availability below 1,000 m^3/yr (based on long-term average runoff) or as having a ratio of withdrawals to long-term average annual runoff above 0.4. These basins are located in Africa, the Mediterranean region, the Near East, South Asia, Northern China, Australia, the USA, Mexico, north-eastern Brazil, and the western coast of South America (Figure 3.2). Estimates of the population living in such severely stressed basins range from 1.4 billion to 2.1 billion (Vörösmarty et al., 2000; Alcamo et al., 2003a, b; Oki et al., 2003a; Arnell, 2004b). In water-scarce areas, people and ecosystems are particularly vulnerable to decreasing and more variable precipitation due to climate change. For example, in the Huanghe River basin in China (Yang et al., 2004), the combination of increasing irrigation water consumption facilitated by reservoirs, and decreasing precipitation associated with global El Niño-Southern Oscillation (ENSO) events over the past half century, has resulted in water scarcity (Wang et al., 2006). The irrigation-dominated Murray-Darling Basin in Australia suffers from decreased water inflows to wetlands and high salinity due to irrigation water use, which affects aquatic ecosystems (Goss, 2003; see also Chapter 11, Section 11.7).

Current adaptation

At the Fourth World Water Forum held in Mexico City in 2006, many of the involved groups requested the inclusion of climate change in Integrated Water Resources Management (World Water Council, 2006). In some countries (e.g., Caribbean, Canada, Australia, Netherlands, UK, USA and Germany), adaptation procedures and risk management practices for the water sector have already been developed that take into account climate change impacts on freshwater systems (compare with Section 3.6).

3.3 Assumptions about future trends

In Chapter 2, scenarios of the main drivers of climate change and their impacts are presented. This section describes how the driving forces of freshwater systems are assumed to develop in the future, with a focus on the dominant drivers during the 21st century. Climate-related and non-climatic drivers are distinguished. Assumptions about future trends in non-climatic drivers are necessary in order to assess the vulnerability of freshwater systems to climate change, and to compare the relative importance of climate change impacts and impacts due to changes in non-climatic drivers.

3.3.1 Climatic drivers

Projections for the future

The most dominant climatic drivers for water availability are precipitation, temperature, and evaporative demand (determined by net radiation at ground level, atmospheric humidity, wind speed, and temperature). Temperature is particularly important in snow-dominated basins and in coastal areas (due to the impact of temperature on sea level).

The following summary of future climate change is taken from the Working Group I Fourth Assessment Report (WGI AR4), Chapter 10 (Meehl et al., 2007). The most likely global average surface temperature increase by the 2020s is around 1°C relative to the pre-industrial period, based on all the IPCC Special Report on Emissions Scenarios (SRES; Nakićenović and Swart, 2000) scenarios. By the end of the 21st century, the most likely increases are 3 to 4°C for the A2 emissions scenario and around 2°C for B1 (Figure 10.8). Geographical patterns of projected warming show the greatest temperature increases at high northern latitudes and over land (roughly twice the global average temperature increase) (Chapter 10, Executive summary, see also Figure 10.9). Temperature increases are projected to be stronger in summer than in winter except for Arctic latitudes (Figure 10.9). Evaporative demand is likely to increase almost everywhere (Figures 10.9 and 10.12). Global mean sea-level rise is expected to reach between 14 and 44 cm within this century (Chapter 10, Executive summary). Globally, mean precipitation will increase due to climate change. Current climate models tend to project increasing precipitation at high latitudes and in the tropics (e.g., the south-east monsoon region and over the tropical Pacific) and decreasing precipitation in the sub-tropics (e.g., over much of North Africa and the northern Sahara) (Figure 10.9).

While temperatures are expected to increase during all seasons of the year, although with different increments, precipitation may increase in one season and decrease in another. A robust finding is that precipitation variability will increase in the future (Trenberth et al., 2003). Recent studies of 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, also over many areas where means are likely to decrease (Christensen and Christensen, 2003, Kundzewicz et al., 2006). The number of wet days in Europe is projected to decrease (Giorgi et al., 2004), which leads to longer dry periods except in the winters of western and central Europe. An increase in the number of days with intense precipitation has been projected across most of Europe, except for the south (Kundzewicz et al., 2006). Multi-model simulations with nine global climate models for the SRES A1B, A2, and B1 scenarios show precipitation intensity (defined as annual precipitation divided by number of wet days) increasing strongly for A1B and A2, and slightly less strongly for B1, while the annual maximum number of consecutive dry days is expected to increase for A1B and A2 only (WGI AR4, Figure 10.18).

Uncertainties

Uncertainties in climate change projections increase with the length of the time horizon. In the near term (e.g., the 2020s), climate model uncertainties play the most important role; while over longer time horizons, uncertainties due to the selection of emissions scenario become increasingly significant (Jenkins and Lowe, 2003).

General Circulation Models (GCMs) are powerful tools accounting for the complex set of processes which will produce future climate change (Karl and Trenberth, 2003). However, GCM projections are currently subject to significant uncertainties in the modelling process (Mearns et al., 2001; Allen and Ingram, 2002; Forest et al., 2002; Stott and Kettleborough, 2002), so that climate projections are not easy to incorporate into hydrological impact studies (Allen and Ingram, 2002). The Coupled Model Intercomparison Project analysed outputs of eighteen GCMs (Covey et al., 2003). Whereas most GCMs had difficulty producing precipitation simulations consistent with observations, the temperature simulations generally agreed well. Such uncertainties produce biases in the simulation of river flows when using direct GCM outputs representative of the current time horizon (Prudhomme, 2006).

For the same emissions scenario, different GCMs produce different geographical patterns of change, particularly with respect to precipitation, which is the most important driver for freshwater resources. As shown by Meehl et al. (2007), the agreement with respect to projected changes of temperature is much higher than with respect to changes in precipitation (WGI AR4, Chapter 10, Figure 10.9). For precipitation changes by the end of the 21st century, the multi-model ensemble mean exceeds the inter-model standard deviation only at high latitudes. Over several regions, models disagree in the sign of the precipitation change (Murphy et al., 2004). To reduce uncertainties, the use of numerous runs from different GCMs with varying model parameters i.e., multi-ensemble runs (see Murphy et al., 2004), or thousands of runs from a single GCM (as from the climateprediction.net experiment; see Stainforth et al., 2005), is often recommended. This allows the construction of conditional probability scenarios of future changes (e.g., Palmer and

Räisänen, 2002; Murphy et al., 2004). However, such large ensembles are difficult to use in practice when undertaking an impact study on freshwater resources. Thus, ensemble means are often used instead, despite the failure of such scenarios to accurately reproduce the range of simulated regional changes, particularly for sea-level pressure and precipitation (Murphy et al., 2004). An alternative is to consider a few outputs from several GCMs (e.g. Arnell (2004b) at the global scale, and Jasper et al. (2004) at the river basin scale).

Uncertainties in climate change impacts on water resources are mainly due to the uncertainty in precipitation inputs and less due to the uncertainties in greenhouse gas emissions (Döll et al., 2003; Arnell, 2004b), in climate sensitivities (Prudhomme et al., 2003), or in hydrological models themselves (Kaspar, 2003). The comparison of different sources of uncertainty in flood statistics in two UK catchments (Kay et al., 2006a) led to the conclusion that GCM structure is the largest source of uncertainty, next are the emissions scenarios, and finally hydrological modelling. Similar conclusions were drawn by Prudhomme and Davies (2007) regarding mean monthly flows and low flow statistics in Britain.

Incorporation 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, e.g., as available from the IPCC Data Distribution Centre (www.ipcc-data.org). In many impact studies, time series of observed climate values are adjusted with the computed change in climate variables to obtain scenarios that are consistent with present-day conditions. These adjustments aim to minimise the error in 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 differences between the observed values and those computed by climate models for the present day are substantial. Model outputs can be biased, and changes in runoff can be underestimated (e.g., Arnell et al. (2003) in Africa and Prudhomme (2006) in Britain). Changes in interannual or daily variability of climate variables are often not taken into account in hydrological impact studies. This leads to an underestimation of future floods, droughts, and irrigation water requirements.

Another problem in the use of GCM outputs is the mismatch of spatial grid scales between GCMs (typically a few hundred kilometres) and hydrological processes. Moreover, the resolution of global models precludes their simulation of realistic circulation patterns that lead to extreme events (Christensen and Christensen, 2003; Jones et al., 2004). To overcome these problems, techniques that downscale GCM outputs to a finer spatial (and temporal) resolution have been developed (Giorgi et al., 2001). These are: dynamical downscaling techniques, based on physical/dynamical links between the climate at 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 in statistical downscaling is that the statistical relationships identified for the current climate will remain valid under changes in future conditions. Downscaling techniques may allow modellers to incorporate future changes in daily variability (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, 2006). 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 (United Nations, 2003). Water resources, both in quantity and quality, are influenced by land-use change, the construction and management of reservoirs, pollutant emissions, and water and wastewater treatment. Water use is driven by changes in population, food consumption, economic policy (including water pricing), technology, lifestyle, and society's views of the value of freshwater ecosystems. Vulnerability of freshwater systems to climate change also depends on water management. It can be expected that the paradigm of Integrated Water Resources Management will be increasingly followed around the world (United Nations, 2002; World Bank, 2003; World Water Council, 2006), which will move water, as a resource and a habitat, into the centre of policy making. This is likely to decrease the vulnerability of freshwater systems to climate change.

Chapter 2 (this volume) provides an overview of the future development of non-climatic drivers, including: population, economic activity, land cover, land use, and sea level, and focuses on the SRES scenarios. In this section, assumptions about key freshwater-specific drivers for the 21st century are discussed: reservoir construction and decommissioning, wastewater reuse, desalination, pollutant emissions, wastewater treatment, irrigation, and other water-use drivers.

In developing countries, new reservoirs will be built in the future, even though their number is likely to be small compared with the existing 45,000 large dams (World Commission on Dams, 2000; Scudder, 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 (Gleick, 2000; Howard, 2000). Consideration of environmental flow requirements may lead to modified reservoir operations so that the human use of the water resources might be restricted.

Increased future wastewater use and desalination are likely mechanisms for increasing water supply in semi-arid and arid regions (Ragab and Prudhomme, 2002; Abufayed et al., 2003). The cost of desalination has been declining, and desalination has been considered as a water supply option for inland towns (Zhou and Tol, 2005). However, there are unresolved concerns about the environmental impacts of impingement and entrainment of marine organisms, the safe disposal of highly concentrated brines that can also contain other chemicals used in the desalination process, and high energy consumption. These have negative impacts on costs and the carbon footprint, and may hamper the expansion of desalination (Cooley et al., 2006).

Wastewater treatment is an important driver of water quality, and an increase in wastewater treatment in both developed and developing countries could 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, should lead to a reduction in point-source nutrient inputs to 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, increases in point emissions of nutrients, heavy metals, and organic micro-pollutants are expected. With heavier rainfall, non-point pollution could increase in all countries.

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 nitrogen fertiliser use to reach 110 to 140 Mt by 2050 as compared to 90 Mt in 2000 (Millennium Ecosystem Assessment, 2005a). In three of the four scenarios, total nitrogen load increases at the global scale, while in the fourth, TechnoGarden, scenario (similar to the SRES B1 scenario), there is a reduction of atmospheric nitrogen deposition as compared to today, so that the total nitrogen load to the freshwater system would decrease. Diffuse emissions of nutrients and pesticides from agriculture are likely to continue to be an important water quality issue in developed countries, and are very likely to increase in developing countries, thus critically affecting water quality.

The most important drivers of water use are population and economic development, and also changing societal views on the value of water. The latter refers to such issues as the prioritisation of domestic and industrial water supply over irrigation water supply, and the extent to which water-saving technologies and water pricing are adopted. In all four Millennium Ecosystems Assessment scenarios, per capita domestic water use in 2050 is rather similar in all world regions, around 100 m^3/yr, i.e., the European average in 2000 (Millennium Ecosystem Assessment, 2005b). This assumes a very strong increase in usage in Sub-Saharan Africa (by a factor of five) and smaller increases elsewhere, except for developed countries (OECD), where per capita domestic water use is expected to decline further (Gleick, 2003). In addition to these scenarios, many other plausible scenarios of future domestic and industrial water use exist which can differ strongly (Seckler et al., 1998; Alcamo et al., 2000, 2003b; Vörösmarty et al., 2000).

The future extent of irrigated areas is the dominant driver of future irrigation water use, together with cropping intensity and irrigation water-use efficiency. According to the Food and Agriculture Organization (FAO) agriculture projections, developing countries (with 75% of the global irrigated area) are likely to expand their irrigated area until 2030 by 0.6%/yr, while the cropping intensity of irrigated land will increase from 1.27 to 1.41 crops/yr, and irrigation water-use efficiency will increase slightly (Bruinsma, 2003). These estimates do not take into account climate change. Most of this expansion is projected to occur in already water-stressed areas, such as southern Asia, northern China, the Near East, and North Africa. A much smaller expansion of irrigated areas, however, is assumed in all four scenarios of the Millennium Ecosystem Assessment, with global growth rates of only 0 to 0.18%/yr until 2050. After 2050, the irrigated area is assumed to stabilise or to slightly decline in all scenarios except Global Orchestration (similar to the SRES A1 scenario) (Millennium Ecosystem Assessment, 2005a).

3.4 Key future impacts and vulnerabilities

3.4.1 Surface waters

Since the TAR, over 100 studies of climate change effects on river flows have been published in scientific journals, and many more have been reported in internal reports. However, studies still tend to be heavily focused on Europe, North America, and Australasia. Virtually all studies use a 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 and Bugmann, 2005; Kay et al., 2006a). A number of global-scale assessments (e.g., Manabe et al., 2004a, b; Milly et al., 2005, Nohara et al., 2006) directly use climate model simulations of river runoff, but the reliability of estimated changes is dependent on the rather poor ability of the climate model to simulate 20th century runoff reliably.

Methodological advances since the TAR 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., 2004; Meleshko et al., 2004; Payne et al., 2004; Kay et al., 2006b; Fowler et al., 2007; Graham et al., 2007a, b; Prudhomme and Davies, 2007), 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; Wilby, 2005; Kay et al., 2006a, b). However, the largest contribution to uncertainty in future river flows comes from the variations between the GCMs used to derive the scenarios.

Figure 3.3 provides an indication of the effects of future climate change on long-term average annual river runoff by the 2050s, across the world, under the A2 emissions scenario and different climate models used in the TAR (Arnell, 2003a). Obviously, even for large river basins, climate change scenarios from different climate models may result in very different projections of future runoff change (e.g., in Australia, South America, and Southern Africa).

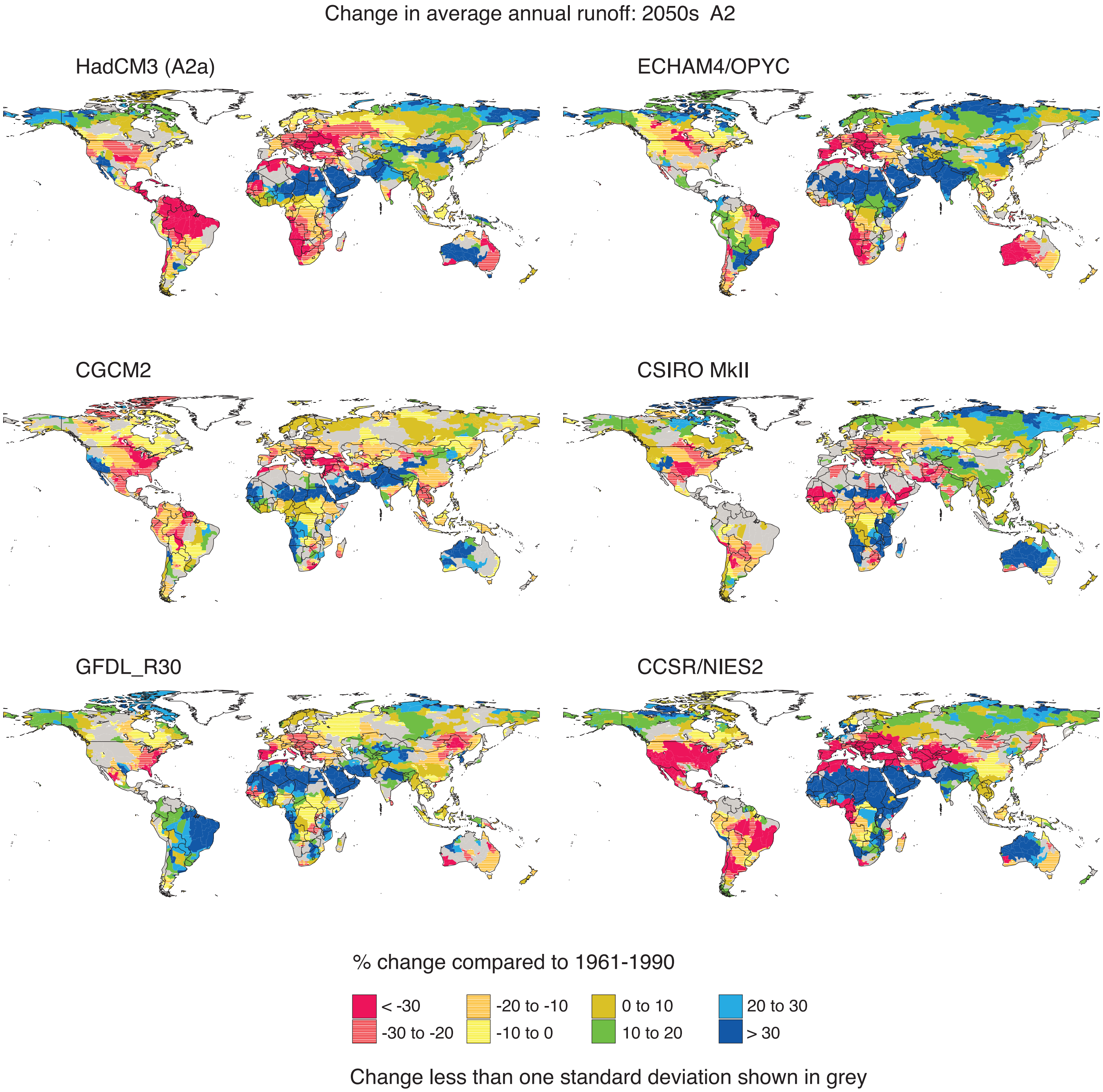

Figure 3.3. *Change in average annual runoff by the 2050s under the SRES A2 emissions scenario and different climate models (Arnell, 2003a).*

Figure 3.4 shows the mean runoff change until 2050 for the SRES A1B scenario from an ensemble of twenty-four climate model runs (from twelve different GCMs) (Milly et al., 2005). Almost all model runs agree at least with respect to the direction of runoff change in the high latitudes of North America and Eurasia, with increases of 10 to 40%. This is in agreement with results from a similar study of Nohara et al. (2006), which showed that the ensemble mean runoff change until the end of the 21st century (from nineteen GCMs) is smaller than the standard deviation everywhere except at northern high latitudes. With higher uncertainty, runoff can be expected to increase in the wet tropics. Prominent regions, with a rather strong agreement between models, of decreasing runoff (by 10 to 30%) include the Mediterranean, southern Africa, and western USA/northern Mexico. In general, between the late 20th century and 2050, the areas of decreased runoff expand (Milly et al., 2005).

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 projections for the European Alps (Eckhardt and Ulbrich, 2003; Jasper et al., 2004; Zierl and Bugmann, 2005), the Himalayas (Singh, 2003; Singh and Bengtsson, 2004), western North America (Loukas et al.,

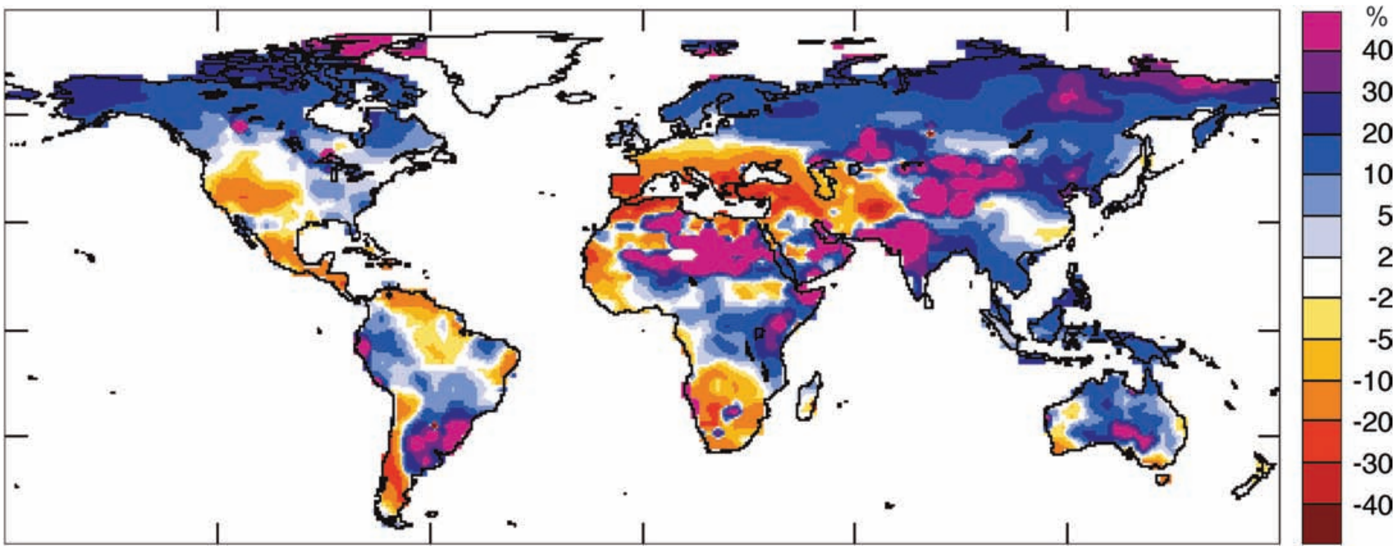

Figure 3.4. *Change in annual runoff by 2041-60 relative to 1900-70, in percent, under the SRES A1B emissions scenario and based on an ensemble of 12 climate models. Reprinted by permission from Macmillan Publishers Ltd. [Nature] (Milly et al., 2005), copyright 2005.*

2002a, b; Christensen et al., 2004; Dettinger et al., 2004; Hayhoe et al., 2004; Knowles and Cayan, 2004; Leung et al., 2004; Payne et al., 2004; Stewart et al., 2004; VanRheenen et al., 2004; Kim, 2005; Maurer and Duffy, 2005), central North America (Stone et al., 2001; Jha et al., 2004), eastern North America (Frei et al., 2002; Chang, 2003; Dibike and Coulibaly, 2005), the entire Russian territory (Shiklomanov and Georgievsky, 2002; Bedritsky et al., 2007), and Scandinavia and Baltic regions (Bergström et al., 2001; Andreasson et al., 2004; Graham, 2004). The effect is greatest at lower elevations (where snowfall is more marginal) (Jasper et al., 2004; Knowles and Cayan, 2004), and in many cases peak flow would occur at least a month earlier. Winter flows increase and summer flows decrease.

Many rivers draining glaciated regions, particularly in the Hindu Kush-Himalaya and the South-American Andes, are sustained by glacier melt during the summer season (Singh and Kumar, 1997; Mark and Seltzer, 2003; Singh, 2003; Barnett et al., 2005). Higher temperatures generate increased glacier melt. 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 (see Chapter 1), river flows are increased in the short term, but the contribution of glacier melt will gradually decrease over the next few decades.

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 (Burlando and Rosso, 2002; Evans and Schreider, 2002; Menzel and Burger, 2002; Arnell, 2003b, 2004a; Boorman, 2003a; Booij, 2005) 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 the 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 river inflows and precipitation onto and evaporation from the lake. Impact assessments of the Great Lakes of North America show changes in water levels of between −1.38 m and +0.35 m by the end of the 21st century (Lofgren et al., 2002; Schwartz et al., 2004). Shiklomanov and Vasiliev (2004) suggest that the level of the Caspian Sea will change in the range of 0.5 to 1.0 m. In another study by Elguindi and Giorgi (2006), the levels in the Caspian Sea are estimated to drop by around 9 m by the end of the 21st century, due largely to increases in evaporation. Levels in some lakes represent a changing balance between inputs and outputs and, under one transient scenario, levels in Lake Victoria would initially fall as increases in evaporation offset changes in precipitation, but subsequently rise as the effects of increased precipitation overtake the effects of higher evaporation (Tate et al., 2004).

Increasing winter temperature considerably changes the ice regime of water bodies in northern regions. Studies made at the State Hydrological Institute, Russia, comparing the horizon of 2010 to 2015 with the control period 1950 to 1979, show that ice cover duration on the rivers in Siberia would be shorter by 15 to 27 days and maximum ice cover would be thinner by 20 to 40% (Vuglinsky and Gronskaya, 2005).

Model studies show that 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 and 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.

Carbon dioxide enrichment of the atmosphere has two potential competing implications for evapotranspiration, and hence water balance and runoff. First, higher CO_2 concentrations can lead to reduced evaporation, as the stomata, through which evaporation from plants takes place, conduct less water. Second, higher CO_2 concentrations can lead to increased plant growth and thus leaf area, and hence a greater total evapotranspiration from the area. The relative magnitudes of these two effects, however, vary between plant types and also depend on other influences such as the availability of nutrients and the effects of changes in temperature and water availability. Accounting for the effects of CO_2 enrichment on runoff requires the incorporation of a dynamic vegetation model into a hydrological model. A small number of models now do this (Rosenberg et al., 2003; Gerten et al., 2004; Gordon and Famiglietti, 2004; Betts et al., 2007), but are usually at the GCM (and not catchment) scale. Although studies with equilibrium vegetation models suggest that increased leaf area may offset stomatal closure (Betts et al., 1997; Kergoat et al., 2002), studies with dynamic global vegetation models indicate that stomatal responses dominate the effects of leaf area increase. Taking into account CO_2-induced changes in vegetation, global mean runoff under a $2{\times}CO_2$ climate has been simulated to increase by approximately 5% as a result of reduced evapotranspiration due to CO_2enrichment alone ('physiological forcing') (Betts et al., 2007; Leipprand and Gerten, 2006). This may be compared to (often much larger) changes at the river basin scale (Figures 3.3, 3.4, and 3.7), and global values of runoff change. For example, global mean runoff has been simulated to increase by 5%-17% due to climate change alone in an ensemble of 143 $2{\times}CO_2$ GCM simulations (Betts et al., 2006).

3.4.2 Groundwater

The demand for groundwater is likely to increase in the future, the main reason being increased water use globally. Another reason may be the need to offset declining surface water availability due to increasing precipitation variability in general and reduced summer low flows in snow-dominated basins (see Section 3.4.3).

Climate change will affect groundwater recharge rates, i.e., the renewable groundwater resource, and groundwater levels. However, even knowledge of current recharge and levels in both developed and developing countries is poor. There has been very little research on the impact of climate change on groundwater, including the question of how climate change will affect the relationship between surface waters and aquifers that are hydraulically connected (Alley, 2001). Under certain circumstances (good hydraulic connection of river and aquifer, low groundwater recharge rates), changes in river level influence groundwater levels much more than changes in groundwater recharge (Allen et al., 2003). As a result of climate change, in many aquifers of the world the spring recharge shifts towards winter, and summer recharge declines. In high latitudes, thawing of permafrost will cause changes in groundwater level and quality. Climate change may lead to vegetation changes which also affect groundwater recharge. Also, with increased frequency and magnitude of floods, groundwater recharge may increase, in particular 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, and alluvial aquifers are mainly recharged by floods (Al-Sefry et al., 2004). Accordingly, an assessment of climate change impact on groundwater recharge should include the effects of changed precipitation variability and inundation areas (Khiyami et al., 2005).

According to the results of a global hydrological model, groundwater recharge (when averaged globally) increases less than total runoff (Döll and Flörke, 2005). While total runoff (groundwater recharge plus fast surface and sub-surface runoff) was computed to increase by 9% between the reference climate normal 1961 to 1990 and the 2050s (for the ECHAM4 interpretation of the SRES A2 scenario), groundwater recharge increases by only 2%. For the four climate scenarios investigated, computed groundwater recharge decreases dramatically by more than 70% in north-eastern Brazil, south-west Africa and along the southern rim of the Mediterranean Sea (Figure 3.5). In these areas of decreasing total runoff, the percentage decrease of groundwater recharge is higher than that of total runoff, which is due to the model assumption that in semi-arid areas groundwater recharge only occurs if daily precipitation exceeds a certain threshold. However, increased variability of daily precipitation was not taken into account in this study. Regions with groundwater recharge increases of more than 30% by the 2050s include the Sahel, the Near East, northern China, Siberia, and the western USA. Although rising watertables in dry areas are usually beneficial, they might cause problems, e.g., in towns or agricultural areas (soil salinisation, wet soils). A comparison of the four scenarios in Figure 3.5 shows that lower emissions do not lead to significant changes in groundwater recharge, and that in some regions, e.g., Spain and Australia, the differences due to the two climate models are larger than the differences due to the two emissions scenarios.

The few studies of climate impacts on groundwater for various aquifers show very site-specific results. 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 are projected to decrease by as much as 50%, potentially leading to water quality problems and groundwater withdrawal restrictions (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 temperature, the sensitivity of groundwater levels to temperature increases (Chen et al., 2004), particularly where the confining layer is thin. In higher latitudes, the sensitivity of groundwater and runoff to increasing temperature is greater because of increasing biomass and leaf area index (improved growth conditions and increased evapotranspiration). For an unconfined aquifer located in humid north-eastern USA,

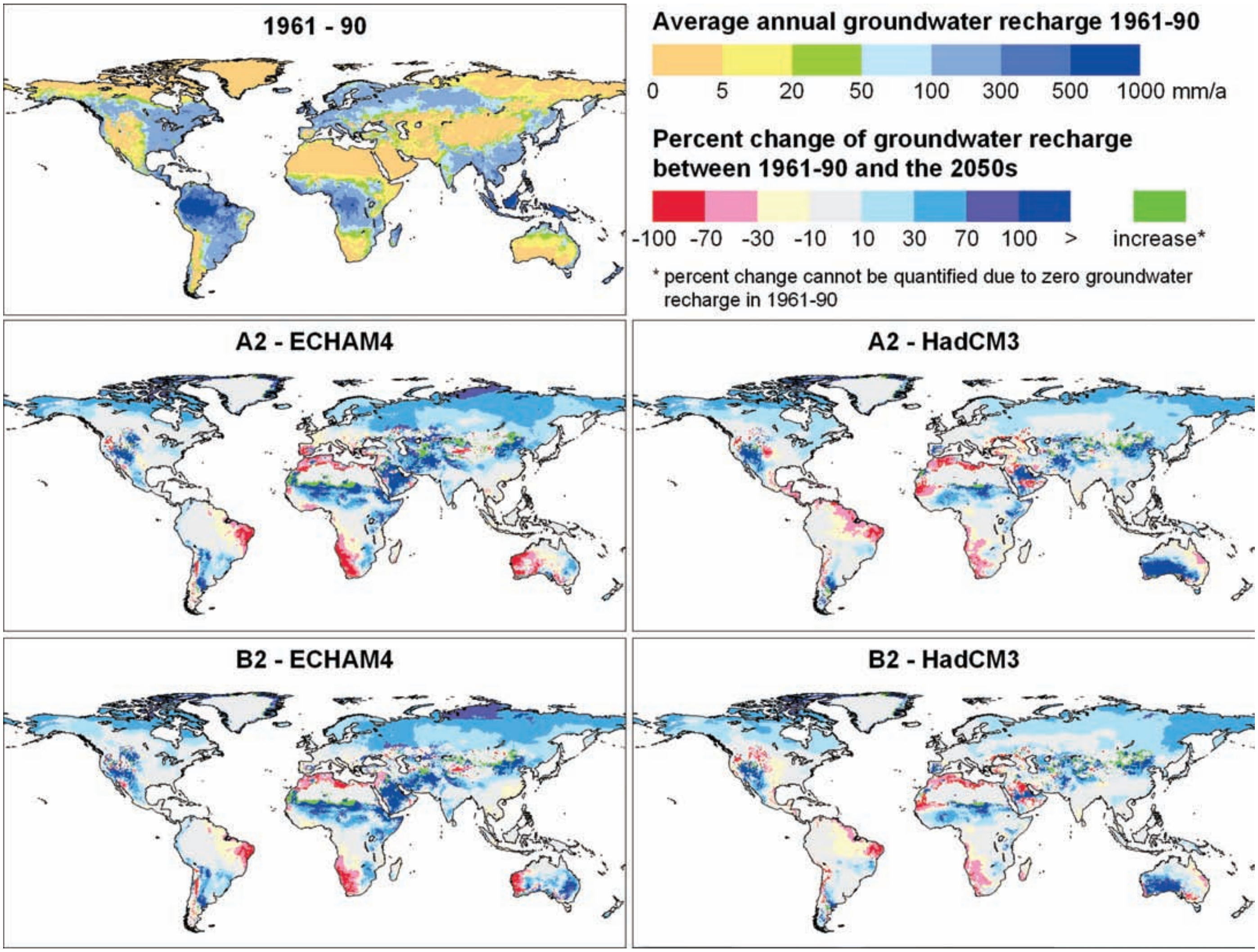

Figure 3.5. *Simulated impact of climate change on long-term average annual diffuse groundwater recharge. Percentage changes of 30 year averages groundwater recharge between present-day (1961 to 1990) and the 2050s (2041 to 2070), as computed by the global hydrological model WGHM, applying four different 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 and Flörke, 2005).*

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 of which strongly depend on the climate model used to compute the groundwater model input (Kirshen, 2002).

Climate change is likely to have a strong impact on saltwater intrusion into aquifers as well as on the salinisation 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. For two small, 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 m to 28 m for a sea-level rise of only 0.1 m (Bobba et al., 2000). Any decrease in groundwater recharge will exacerbate the effect of sea-level rise. In inland aquifers, a decrease in groundwater recharge can lead to saltwater intrusion of neighbouring saline aquifers (Chen et al., 2004), and increased evapotranspiration in semi-arid and arid regions may lead to the salinisation of shallow aquifers.

3.4.3 Floods and droughts

A warmer climate, with its increased climate variability, will increase the risk of both floods and droughts (Wetherald and Manabe, 2002; Table SPM2 in IPCC, 2007). As there are a number of climatic and non-climatic drivers influencing flood and drought impacts, the realisation of risks depends on several factors. Floods include river floods, flash floods, urban floods and sewer floods, and can be caused by intense and/or long-lasting precipitation, snowmelt, dam break, or reduced conveyance due to ice jams or landslides. Floods depend on precipitation intensity, volume, timing, antecedent conditions of rivers and their drainage basins (e.g., presence of snow and ice, soil character, wetness, urbanisation, and existence of dikes, dams, or reservoirs). Human encroachment into flood plains and lack of flood response plans increase the damage potential.

The term drought may refer to meteorological drought (precipitation well below average), hydrological drought (low river flows and water levels in rivers, lakes and groundwater), agricultural drought (low soil moisture), and environmental drought (a combination of the above). The socio-economic impacts of droughts may arise from the interaction between natural conditions and human factors, such as changes in land use and land cover, water demand and use. Excessive water withdrawals can exacerbate the impact of drought.

A robust result, consistent across climate model projections, is that higher precipitation extremes in warmer climates are very likely to occur (see Section 3.3.1). Precipitation intensity increases almost everywhere, but particularly at mid- and high latitudes where mean precipitation also increases (Meehl et al., 2005, WGI AR4, Chapter 10, Section 10.3.6.1). This directly affects the risk of flash flooding and urban flooding. Storm drainage systems have to be adapted to accommodate increasing rainfall intensity resulting from climate change (Waters et al., 2003). An increase of droughts over low latitudes and mid-latitude continental interiors in summer is likely (WGI AR4, Summary for Policymakers, Table SPM.2), but sensitive to model land-surface formulation. Projections for the 2090s made by Burke et al. (2006), using the HadCM3 GCM and the SRES A2 scenario, show regions of strong wetting and drying with a net overall global drying trend. For example, the proportion of the land surface in extreme drought, globally, is predicted to increase by the a factor of 10 to 30; from 1-3 % for the present day to 30% by the 2090s. The number of extreme drought events per 100 years and mean drought duration are likely to increase by factors of two and six, respectively, by the 2090s (Burke et al., 2006). A decrease in summer precipitation in southern Europe, accompanied by rising temperatures, which enhance evaporative demand, would inevitably lead to reduced summer soil moisture (Douville et al., 2002) and more frequent and more intense droughts.

As temperatures rise, the likelihood of precipitation falling as rain rather than snow increases, especially in areas with temperatures near to 0°C in autumn and spring (WGI AR4, Summary for Policymakers). Snowmelt is projected to be earlier and less abundant in the melt period, and this may lead to an increased 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 melt water from 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, will be adverse and severe. Drought problems are projected for regions which depend heavily on glacial melt water for their main dry-season water supply (Barnett et al., 2005). In the Andes, glacial melt water supports river flow and water supply for tens of millions of people during the long dry season. Many small glaciers, e.g., in Bolivia, Ecuador, and Peru (Coudrain et al., 2005), will disappear within the next few decades, adversely affecting people and ecosystems. Rapid melting of glaciers can lead to flooding of rivers and to the formation of glacial melt-water lakes, which may pose a serious threat of outburst floods (Coudrain et al., 2005). The entire Hindu Kush-Himalaya ice mass has decreased in the last two decades. Hence, water supply in areas fed by glacial melt water from the Hindu Kush and Himalayas, on which hundreds of millions of people in China and India depend, will be negatively affected (Barnett et al., 2005).

Under the IPCC IS92a emissions scenario (IPCC, 1992), which is similar to the SRES A1 scenario, significant changes in flood or drought risk are expected in many parts of Europe (Lehner et al., 2005b). The regions most prone to a rise in flood frequencies are northern and north-eastern Europe, while southern and south-eastern Europe show significant increases in drought frequencies. This is the case for climate change as computed by both the ECHAM4 and HadCM3 GCMs. Both models agree in their estimates that by the 2070s, a 100-year drought of today's magnitude would return, on average, more frequently than every 10 years in parts of Spain and Portugal, western France, the Vistula Basin in Poland, and western Turkey (Figure 3.6). Studies indicate a decrease in peak snowmelt floods by the 2080s in parts of the UK (Kay et al., 2006b) despite an overall increase in rainfall.

Results of a recent study (Reynard et al., 2004) 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 on which GCM is used, and on the importance of snowmelt contribution 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).

A sensitivity study by Cunderlik and Simonovic (2005) for a catchment in Ontario, Canada, projected a decrease in snowmelt-induced floods, while an increase in rain-induced floods is anticipated. The variability of annual maximum flow is projected to increase.

Palmer and Räisänen (2002) analysed GCM-modelled differences in winter precipitation between the control run and around the time of CO_2 doubling. A considerable increase in the risk of a very wet winter in Europe and a very wet monsoon season in Asia was found. The probability of total boreal winter precipitation exceeding two standard deviations above normal is projected to increase considerably (even five- to seven-fold) over large areas of Europe, with likely consequences for winter flood hazard.

Milly et al. (2002) demonstrated that, for fifteen out of sixteen large basins worldwide, the control 100-year peak volumes (at the monthly time-scale) are 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 with a large uncertainty in these projections. Yet, in many temperate regions, the snowmelt contribution to spring floods is likely to decline on average (Zhang et al., 2005). Future changes in the joint probability of extremes have been considered, such as soil moisture and flood risk (Sivapalan et al., 2005), and 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., 2004a). The flooded area in Bangladesh is projected to increase at least by 23-29% with a global temperature rise of 2°C (Mirza, 2003). Up to 20% of the world's population live in river basins that are likely to be affected by increased flood hazard by the 2080s in the course of global warming (Kleinen and Petschel-Held, 2007).

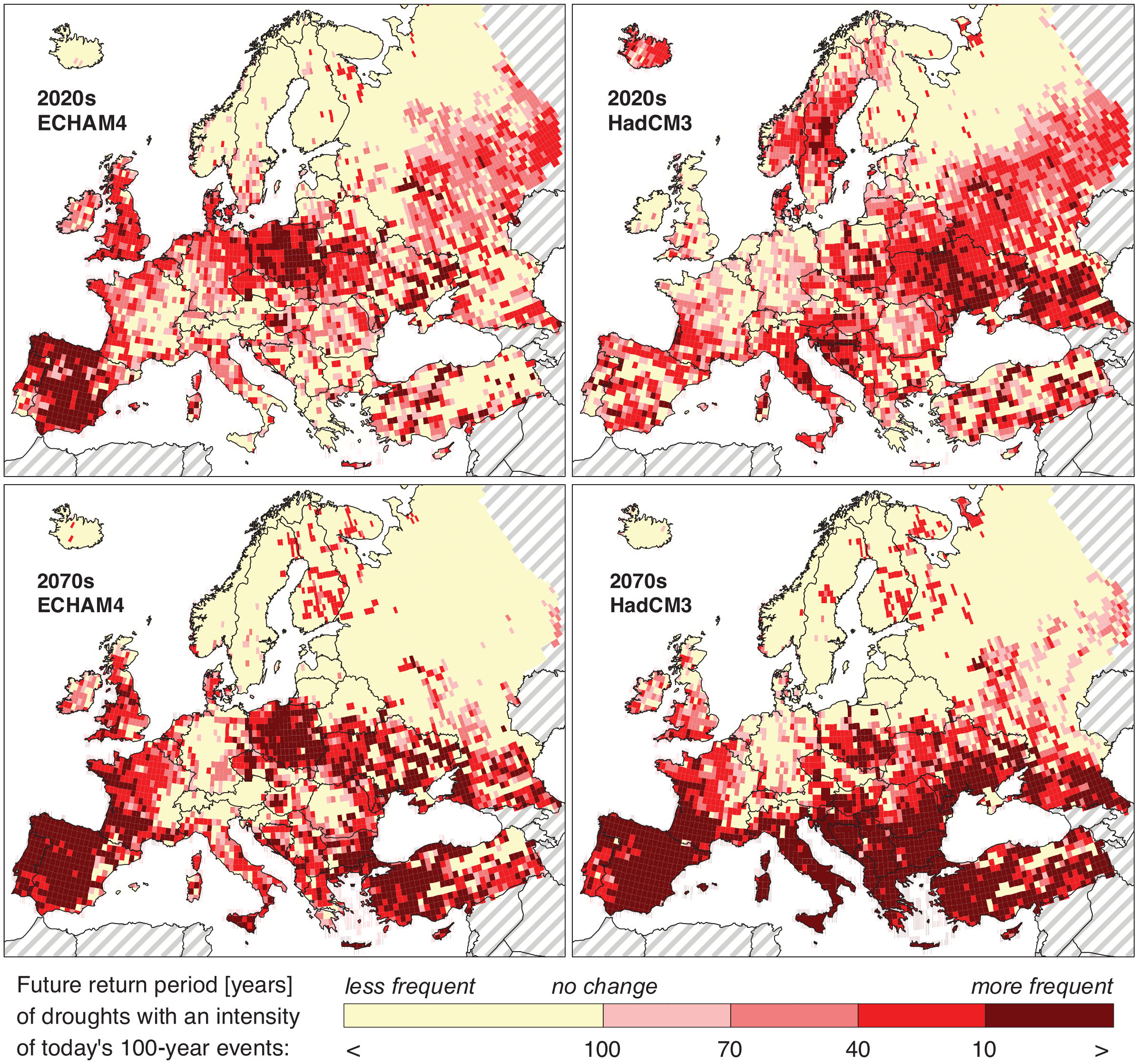

Figure 3.6. *Change in the recurrence of 100-year droughts, based on comparisons between climate and water use in 1961 to 1990 and simulations for the 2020s and 2070s (based on the ECHAM4 and HadCM3 GCMs, the IS92a emissions scenario and a business-as-usual water-use scenario). Values calculated with the model WaterGAP 2.1 (Lehner et al., 2005b).*

3.4.4 Water quality

Higher water temperature and variations in runoff are likely to produce adverse changes in water quality affecting human health, ecosystems, and water use (Patz, 2001; Lehman, 2002; O'Reilly et al., 2003; Hurd et al., 2004). Lowering of the water levels in rivers and lakes will lead to the re-suspension of bottom sediments and liberating compounds, with negative effects on water supplies (Atkinson et al., 1999). More intense rainfall will lead to an increase in suspended solids (turbidity) in lakes and reservoirs due to soil fluvial erosion (Leemans and Kleidon, 2002), and pollutants will be introduced (Mimikou et al., 2000; Neff et al., 2000; Bouraoui et al., 2004).

Higher surface water temperatures will promote algal blooms (Hall et al., 2002; Kumagai et al., 2003) and increase the bacteria and fungi content (Environment Canada, 2001). This may lead to a bad odour and taste in chlorinated drinking water and the occurrence of toxins (Moulton and Cuthbert, 2000; Robarts et al., 2005). Moreover, even with enhanced phosphorus removal in wastewater treatment plants, algal growth may increase with warming over the long term (Wade et al., 2002). Due to the high cost and the intermittent nature of algal blooms, 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 negatively affect water quality (Hamilton et al., 2001), possibly rendering a source unusable unless special treatment is introduced (Environment Canada, 2004). Furthermore, higher water temperatures will enhance the transfer of volatile and semi-volatile compounds (e.g., ammonia, mercury, dioxins, pesticides) from surface water bodies to the atmosphere (Schindler, 2001).

In regions where intense rainfall is expected to increase, pollutants (pesticides, organic matter, heavy metals, etc.) will be increasingly washed from soils to water bodies (Fisher, 2000; Boorman, 2003b; Environment Canada, 2004). Higher runoff is expected to mobilise fertilisers and pesticides to water bodies in regions where their application time and low vegetation growth coincide with an increase in runoff (Soil and Water Conservation Society, 2003). Also, acidification in rivers and lakes is expected to increase as a result of acidic atmospheric deposition (Ferrier and Edwards, 2002; Gilvear et al., 2002; Soulsby et al., 2002).

In estuaries and inland reaches with decreasing streamflow, salinity will increase (Bell and Heaney, 2001; Williams, 2001; Beare and Heaney, 2002; Robarts et al., 2005). Pittock (2003) projected the salt concentration in the tributary rivers above irrigation areas in the Murray-Darling Basin in Australia to increase by 13-19% by 2050 and by 21-72% by 2100. Secondary salinisation 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 salinisation. 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 secondary salinisation (Williams, 2001). Water salinisation is expected to be a major problem in small islands suffering from coastal sea water intrusion, and in semi-arid and arid areas with decreasing runoff (Han et al., 1999; Bobba et al., 2000; Ministry for the Environment, 2001;Williams, 2001; Loáiciga, 2003; Chen et al., 2004; Ragab, 2005). Due to sea-level rise, groundwater salinisation will very likely increase.

Water-borne diseases will rise with increases in extreme rainfall (Hall et al., 2002; Hijioka et al., 2002; D'Souza et al., 2004; see also Chapter 8). In regions suffering from droughts, a greater incidence of diarrhoeal and other water-related diseases will mirror the deterioration in water quality (Patz, 2001; Environment Canada, 2004).

In developing countries, the biological quality of water is poor due to the lack of sanitation and proper potabilisation methods and poor health conditions (Lipp et al., 2001; Jiménez, 2003; Maya et al., 2003; WHO, 2004). Hence, climate change will be an additional stress factor that will be difficult to overcome (Magadza, 2000; Kashyap, 2004; Pachauri, 2004). Regrettably, there are no studies analysing the impact of climate change on biological water quality from the developing countries' perspective, i.e., considering organisms typical for developing countries; the effect of using wastewater to produce food; and Helminthiases diseases, endemic only in developing countries, where low-quality water is used for irrigation (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 the facilities are not designed to deal with them. As an example, Cryptosporidium outbreaks following intense rainfall events have forced some developed countries to adopt an additional filtration step in drinking-water plants, representing a 20 to 30% increase in operating costs (AWWA, 2006), but this is not universal practice.

Water quality modifications may also be observed in future as a result of:

- more water impoundments for hydropower (Kennish, 2002; Environment Canada, 2004),
- storm water drainage operation and sewage disposal disturbances in coastal areas due to sea-level rise (Haines et al., 2000),
- increasing water withdrawals from low-quality sources,
- greater pollutant loads due to increased infiltration rates to aquifers or higher runoff to surface waters (as result of high precipitation),
- water infrastructure malfunctioning during floods (GEO-LAC, 2003; DFID, 2004),
- overloading the capacity of water and wastewater treatment plants during extreme rainfall (Environment Canada, 2001),
- increased amounts of polluted storm water.

In areas where amounts of surface water and groundwater recharge are projected to decrease, water quality will also decrease due to lower dilution (Environment Canada, 2004). Unfortunately, in some regions the use of such water may be necessary, even if water quality problems already exist (see Section 3.2). For example, in regions where water with arsenic or fluorine is consumed, due to a lack of alternatives, it may still be necessary to consume the water even if the quality worsens.

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 in Africa, Asia, and Latin America (DFID, 2004). This number will increase with growing populations and wealth, and it will become imperative to use water more efficiently (including reuse). While recognising the convenience of recycling nutrients (Jiménez and Garduño, 2001), it is essential to be aware of the health and environmental risks caused by reusing low-quality water.

In developing countries, vulnerabilities are related to a lack of relevant information, institutional weakness in responding to a changing environment, and the need to mobilise resources. For the world as a whole, vulnerabilities are related to the need to respond proactively to environmental changes under uncertainty. Effluent disposal strategies (under conditions of lower self-purification in warmer water), the design of water and wastewater treatment plants to work efficiently even during extreme climatic conditions, and ways of reusing and recycling water, will need to be reconsidered (Luketina and Bender, 2002; Environment Canada, 2004; Patrinos and Bamzai, 2005).

3.4.5 Erosion and sediment transport

Changes in water balance terms affect many geomorphic processes including erosion, slope stability, channel change, and sediment transport (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 in freshwater habitats.

All studies on soil erosion have suggested that increased rainfall amounts and intensities will lead to greater rates of erosion unless protection measures are taken. 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. Other reasons include:

- changes in plant canopy caused by shifts in plant biomass production associated with moisture regime;
- changes in litter cover on the ground caused by changes in plant residue decomposition rates driven by temperature, in moisture-dependent soil microbial activity, and in plant biomass production rates;
- changes in soil moisture due to shifting precipitation regimes

and evapotranspiration rates, which changes infiltration and runoff ratios;

- soil erodibility changes due to a decrease in soil organic matter concentrations (which lead to a soil structure that is more susceptible to erosion) and to increased runoff (due to increased soil surface sealing and crusting);
- a shift in winter precipitation from non-erosive snow to erosive rainfall due to increasing winter temperatures;
- melting of permafrost, which induces an erodible soil state from a previously non-erodible one;
- shifts in land use made necessary to accommodate new climatic regimes.

Nearing (2001) used output from two GCMs (HadCM3 and the Canadian Centre for Climate Modelling and Analysis CGCM1) and relationships between monthly precipitation and rainfall erosivity (the power of rain to cause soil erosion) to assess potential changes in rainfall erosivity in the USA. The 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 HadCM3 to assess potential changes in rainfall erosivity in the Huanghe 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 of the order of 20 to 60% over the next five decades for two sites in Saxony, Germany. These results are arguably based on significant simplifications with regard to the array of interactions involved in this type of assessment (e.g., biomass production with changing climate). Pruski and Nearing (2002a) simulated erosion for the 21st century at eight locations in the USA using the HadCM3 GCM, and taking into account the primary physical and biological mechanisms affecting erosion. The simulated cropping systems were maize and wheat. The results indicated a complex set of interactions between the several factors that affect the erosion process. Overall, where precipitation increases were projected, estimated erosion increased by 15 to 100%. Where precipitation decreases were projected, the results were more complex due largely to interactions between plant biomass, runoff, and erosion, and either increases or decreases in overall erosion could occur.

A significant potential impact of climate change on soil erosion and sediment generation is associated with the change from snowfall to rainfall. The potential impact may be particularly important in northern climates. Warmer winter temperatures would bring an increasing amount of winter precipitation as rain instead of snow, and erosion by storm runoff would increase. The results described above which use a process-based approach incorporated the effect of a shift from snow to rain due to warming, but the studies did not delineate this specific effect from the general results. Changes in soil surface conditions, such as surface roughness, sealing and crusting, may change with shifts in climate, and hence affect erosion rates.

Zhang and Nearing (2005) evaluated the potential impacts of climate change on soil erosion in central Oklahoma. Monthly projections were used from the HadCM3 GCM, using the SRES A2 and B2 scenarios and GGa1 (a scenario in which greenhouse gases increase by 1%/yr), for the periods 1950 to 1999 and 2070 to 2099. While the HadCM3-projected mean annual precipitation during 2070 to 2099 at El Reno, Oklahoma, decreased by 13.6%, 7.2%, and 6.2% for A2, B2, and GGa1, respectively, the predicted erosion (except for the no-till conservation practice scenario) increased by 18-30% for A2, remained similar for B2, and increased by 67-82% for GGa1. The greater increases in erosion in the GGa1 scenario was attributed to greater variability in monthly precipitation and an increased frequency of large storms in the model simulation. Results indicated that no-till (or conservation tillage) systems can be effective in reducing soil erosion under projected climates.

A more complex, but potentially dominant, factor 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 change. Farmer adaptation may range from shifts in planting, cultivation and harvest dates, to changes in crop type (Southworth et al., 2000; 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 maize towards soybean production. For ten out of eleven regions in 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 (O'Neal et al., 2005). Other land-use 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 has a huge negative impact on susceptibility to runoff and erosion.

Little work has been done on the expected impacts of climate change on sediment loads in rivers and streams. Bouraoui et al. (2004) showed, for southern Finland, that the observed increase in precipitation and temperature was responsible for a decrease in snow cover and increase in winter runoff, which resulted in an increase in modelled suspended sediment loads. Kostaschuk et al. (2002) measured suspended sediment loads associated with tropical cyclones in Fiji, which generated very high (around 5% by volume) concentrations of sediment in the measured flows. The authors hypothesized that an increase in intensity of tropical cyclones brought about by a change in El Niño patterns could increase associated sediment loads in Fiji and across the South Pacific.

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

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. These include the costs of damages and the costs of adaptation (to reduce or avoid damages), as well as benefits that could result from improved water availability in some areas. In addition to 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. Costs and benefits of climate change may take several forms, including increases or decreases in monetary costs, and human and ecosystem impacts, e.g., displacement of households due to flooding, and loss of aquatic species. So far, very few of these costs have been estimated in monetary terms. Efforts to quantify the economic impacts of climate-related changes in water resources are hampered by a lack of data and by the fact that the estimates are highly sensitive to different estimation methods and to different assumptions regarding how changes in water availability will be allocated across various types of water uses, e.g., between agricultural, urban, or in-stream uses (Changnon, 2005; Schlenker et al., 2005; Young, 2005).

With respect to water supply, it is very likely that the costs of climate change will outweigh the benefits. One reason is that precipitation variability is very likely to increase. The impacts of floods and droughts could be tempered by appropriate infrastructure investments, and by changes in water and land-use management, but all of these responses entail costs (US Global Change Research Program, 2000). Another reason is that water infrastructure, use patterns, and institutions have developed in the context of current conditions (Conway, 2005). Any substantial change in the frequency of floods and droughts or in the quantity and quality or seasonal timing of water availability will require adjustments that may be costly not only in monetary terms, but also in terms of societal impacts, including the need to manage potential conflicts among different interest 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. In recent decades, a trend to wetter conditions in parts of southern South America has increased the area inundated by floods, but has also improved crop yields in the Pampa region of Argentina, and has provided new commercial fishing opportunities (Magrin et al., 2005; also see Chapter 13). Increased runoff could also damage areas with a shallow watertable. In such areas, a watertable rise will disturb agricultural use and damage buildings in urban areas. For Russia, for example, the current annual damage caused by shallow watertables is estimated to be US$5-6 billion (Kharkina, 2004) and is likely to increase in the future. In addition, an increase in annual runoff may not lead to a beneficial increase in readily available water resources if the additional runoff is concentrated during the 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 between water demand 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 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 would 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 and losses across different sectors of society. Institutional settings differ significantly both within and between countries, often resulting in substantial differences in the efficiency, equity, and flexibility of water use and infrastructure development (Wichelns et al., 2002; Easter and Renwick, 2004; Orr and Colby, 2004; Saleth and Dinar, 2004; Svendsen, 2005).

In addition, quantity of water is not the only important variable. Changes in water quality and temperature can also 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 increased nutrient and pathogen content of 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 demand. Some of these compete directly with one another in that the 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. Sectoral water demands can be expected to change over time in response to changes in population, settlement patterns, wealth, industrial activity, and technology. For example, rapid urbanization can lead to substantial localised growth in water demand, often making it difficult to meet goals for the provision of a safe, affordable, domestic water supply, particularly in arid regions (e.g., Faruqui et al., 2001). In addition, climate change will probably alter the desired uses of water (demands) as well as actual uses (demands in each sector that are actually met). If climate change results in greater water scarcity relative to demand, adaptation may include technical changes that improve water-use efficiency, demand management (e.g., through metering and pricing), and institutional changes that improve the tradability of water rights. It takes time to implement such changes, so they are likely to become more effective as time passes. Because the availability of water for each type of use may be affected by other competing uses of the resource, a complete analysis of the effects of climate change on human water uses should consider cross-sector interactions, including the impacts of changes in water-use efficiency and intentional transfers of the use of water from one sector to another. For example, voluntary water transfers, including short-term water leasing as well as permanent sales of water rights, generally from agricultural to urban or environmental uses, are becoming increasingly common in the western USA. These water-market transactions can be expected to play a role in facilitating adaptation to climate change (Miller et al., 1997; Easter et al., 1998; Brookshire et al., 2004; Colby et al., 2004).

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 and Rodda, 2003). Given the dominant role of irrigated agriculture in global water use, management practices that increase the productivity of irrigation water use (defined as crop output per unit of consumptive water use) can greatly increase the availability of water for other human and environmental uses (Tiwari and Dinar, 2002). Of all sectoral water demands, the irrigation sector will be affected most strongly by climate change, as well as by changes in the effectiveness of irrigation methods. In areas facing water scarcity, changes in irrigation water use will be driven by the combined effects of changes in irrigation water demand, changes in demands for higher value uses (e.g., for urban areas), future management changes, and changes in availability.

Higher temperatures and increased variability of precipitation would, in general, lead to an increased irrigation water demand, even if the total precipitation during the growing season remains the same. As a result of increased atmospheric CO_2 concentrations, water-use efficiency for some types of plants would increase, which would increase the ratio of crop yield to unit of water input (water productivity – 'more crop per drop'). However, in hot regions, such as Egypt, the ratio may even decline as yields decrease due to heat stress (see Chapter 5).

There are no global-scale studies that attempt to quantify the influence of climate-change-related factors on irrigation water use; only the impact of climate change on optimal growing periods and yield-maximising irrigation water use has been modelled, assuming no change in irrigated area and climate variability (Döll, 2002; Döll et al., 2003). Applying the SRES A2 and B2 scenarios as interpreted by two climate models, these authors found that the optimal growing periods could 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. Different climate models project different worldwide changes in net irrigation requirements, with estimated increases ranging from 1 to 3% by the 2020s and 2 to 7% by the 2070s. The largest global-scale increases in net irrigation requirements result from a climate scenario based on the B2 emissions scenario.

At 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 rain-fed production) foresee a decrease in irrigated areas and withdrawals beyond 2030 for various climate scenarios (Reilly et al., 2003; Thomson et al., 2005b). This result is related to a declining yield gap between irrigated and rain-fed agriculture caused by yield reductions of irrigated crops due to higher temperatures, or yield increases of rain-fed crops due to more precipitation. These studies did not take into account the increasing variability of daily precipitation, such that rain-fed yields are probably overestimated. In a study of maize irrigation in Illinois under profit-maximising 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 and Tornil, 1999). This study also showed that profit-maximising irrigation water use responds more strongly to changes in precipitation than does yield-maximising water use, and that a doubling of atmospheric CO_2 has only a small effect.

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 by 2030 for developing countries. In the four Millennium Ecosystem Assessment scenarios, however, increases at the global scale are much less, as irrigated areas are assumed to increase only between 0% and 6% by 2030 and between 0% and 10% by 2050. The overwhelming water use increases are likely to occur in the domestic and industrial sectors, with increases of water withdrawals by 14-83% by 2050 (Millennium Ecosystem Assessment, 2005a, b). This is based on the idea that the value of water would be much higher for domestic and industrial uses (particularly true under conditions of water stress).

The increase in household water demand (e.g., for garden watering) and industrial water demand due to climate change is likely to be rather small, e.g., less than 5% by the 2050s at selected locations (Mote et al., 1999; Downing et al., 2003). An indirect but small secondary effect on water demand would be the increased electricity demand for cooling of buildings, which would tend to increase water withdrawals for cooling of thermal power plants (see 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/1°C (roughly 2% of current daily per capita use) (Protopapas et al., 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, 2005b). In cold or snow-dominated river basins, atmospheric temperature increases do not only affect freshwater ecosystems via the warming of water (see Chapter 4) but also by causing water-flow alterations. In northern Alberta, Canada, for example, a decrease in ice-jam flooding will lead to the loss of aquatic habitat (Beltaos et al., 2006). Where river discharges decrease seasonally, negative impacts on both freshwater ecosystems and coastal marine ecosystems can be expected. Atlantic salmon in north-west England will be affected negatively by climate change because suitable flow depths during spawning time (which now occur all the time) will, under the SRES A2 scenario, only exist for 94% of the time in the 2080s (Walsh and Kilsby, 2007). Such changes will have implications for ecological flow management and compliance with environmental legislation such as the EU Habitats Directive. In the case of decreased discharge in the western USA, by 2050 the Sacramento and Colorado River deltas could experience a dramatic increase in salinity and subsequent ecosystem disruption and, in the Columbia River system, managers will be faced with the choice of either spring and summer releases for salmon runs, or summer and autumn hydroelectric power production. Extinction of some salmon species due to climate change in the Pacific Northwest may take place regardless of water policy (Barnett et al., 2005).

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 (Justic et al., 2005). While increased river discharge of the Mississippi would increase the frequency of hypoxia (shortage of oxygen) events in the Gulf of Mexico, increased river discharge into the Hudson Bay would lead to the opposite (Justic et al., 2005). The frequency of bird-breeding events in the Macquarie Marshes in the Murray-Darling Basin in Australia is predicted to decrease with reduced streamflow, as the breeding of colonially nesting water-birds requires a certain minimum annual flow. Climate change and reforestation can contribute to a decrease in river discharge, but before 2070 the largest impact can be expected from a shift in rainfall due to decadal-scale climate variability (Herron et al., 2002).

Water availability for socio-economic activities

Climate change is likely to alter river discharge, resulting in important impacts on water availability for instream and out-of-stream uses. Instream uses include hydropower, navigation, fisheries, and recreation. Hydropower impacts for Europe have been estimated using a macro-scale hydrological model. The results indicate that, by the 2070s, under the IS92a emissions scenario, the electricity production potential of hydropower plants existing at the end of the 20th century will increase, by 15-30% in Scandinavia and northern Russia, where between 19% (Finland) and almost 100% (Norway) of the electricity is produced by hydropower (Lehner et al., 2005a). Decreases by 20-50% or more are computed for Portugal, Spain, Ukraine, Bulgaria, and Turkey, where between 10% (Ukraine, Bulgaria) and 39% of the electricity is produced by hydropower (Lehner et al., 2005a). For the whole of Europe (with a 20% hydropower fraction), hydropower potential shows a decrease of 7-12% by the 2070s. In North America, potential reductions in the outflow of the Great Lakes could result in significant economic losses as a result of reduced hydropower generation at Niagara and on the St. Lawrence River (Lofgren et al., 2002). For a CGCM1 model projection with 2°C global warming, Ontario's Niagara and St. Lawrence hydropower generation would decline by 25-35%, resulting in annual losses of Canadian $240 million to $350 million (2002 prices) (Buttle et al., 2004). With the HadCM2 climate model, however, a small gain in hydropower potential (+ 3%) was computed, worth approximately Canadian $25 million/yr. Another study that examined a range of climate model scenarios found that a 2°C global warming could reduce hydropower-generating capacity on the St. Lawrence River by 1% to 17% (LOSLR, 2006). Increased flood periods in the future will disrupt navigation more often, and low flow conditions that restrict the loading of ships may increase, for the Rhine river, from 19 days under current climate conditions to 26-34 days in the 2050s (Middelkoop et al., 2001).

Out-of-stream uses include irrigation, domestic, municipal, and industrial withdrawals, including cooling water for thermal electricity generation. Water availability for withdrawal is a function of runoff, aquifer conditions, 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, the goal of improved safe access to drinking water will be harder to achieve in regions where runoff decreases as a result of climate change. Also, climate change leads to additional costs for the water supply sector, e.g., due to changing water levels affecting water supply infrastructure, which might hamper the extension of water supply services to more people.

Climate-change-induced changes of the seasonal runoff regime and interannual runoff variability can be as important for water availability as changes in the long-term average annual runoff amount if water is not withdrawn from large groundwater bodies or reservoirs (US Global Change Research Program, 2000). 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 et al., 2005). The Rhine, for example, might suffer from a 5 to 12% reduction in summer low flows by the 2050s, which will negatively affect water supply, in particular for thermal power plants (Middelkoop et al., 2001). Studies for the Elbe River Basin have shown that actual evapotranspiration is projected to increase by 2050 (Krysanova and Wechsung, 2002), while river flow, groundwater recharge, crop yield, and 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 climate change have been estimated for China. This cost is low in basins where the current water stress is low (e.g., Changjiang), and high where it is high (e.g., Huanghe River) (Kirshen et al., 2005a). Furthermore, the impact of climate change on water supply costs will increase in the future, not only because of increasing climate change but also due to increasing demand.

A number of global-scale (Alcamo and Henrichs, 2002; Arnell, 2004b), national-scale (Thomson et al., 2005a), and basin-scale assessments (Barnett et al., 2004) show that semi-arid and arid basins are the most vulnerable basins on the globe with respect to water stress. If precipitation decreases, irrigation water demands, which dominate water use in most semi-arid river basins, would increase, and it may become impossible to satisfy all demands. 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 output from a downscaled GCM – the PCM model from the National Center for Atmospheric Research) are so strong that, beyond 2020, not all the present-day water demands (including environmental targets) could be fulfilled even with adapted reservoir management (Barnett et al., 2004). Furthermore, if irrigation use is allowed to increase in response to increased demands, that would amplify the decreases in runoff and streamflow downstream (Eheart and Tornil, 1999). Huffaker (2005) notes that some policies aimed at rewarding improvements in irrigation efficiency allow irrigators to spread a given diversion right to a larger land area. The unintended consequence could be increased consumptive water use that deprives downstream areas of water that would have re-entered the stream as return flow. Such policies could make irrigation no longer feasible in the lower reaches of basins that experience reduced streamflow.

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 (see Box 3.1), and how the costs of this alteration can be assessed.

In western China, earlier spring snowmelt and declining glaciers are likely to reduce water availability for irrigated agriculture (see Chapter 10). For an aquifer in Texas, the 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 et al., 2001). If freshwater supply has to be replaced by desalinated water due to climate change, then the cost of climate change includes the cost of desalination, which is currently around US$1/m^3 for seawater and US$0.6/m^3 for brackish water (Zhou and Tol, 2005), compared to the chlorination cost of freshwater of US$0.02/m^3 and costs between US$0.35 and US$1.9/m^3 for additional supply in a case study in Canada (see Box 3.1). In densely populated coastal areas of Egypt, China, Bangladesh, India, and Southeast Asia (FAO, 2003), desalination costs may be prohibitive.

Most semi-arid river basins in developing countries are more vulnerable to climate change than basins in developed countries, as population, and thus water demand, is expected to grow rapidly in the future and the coping capacity is low (Millennium Ecosystem Assessment, 2005b). Coping capacity is particularly low in rural populations 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, 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, although they might be less prepared for coping with droughts than people in dry basins (Wilhite, 2001).

Global estimates of the number of people living in areas with high water stress differ significantly among studies (Vörösmarty et al., 2000; Alcamo et al., 2003a, b, 2007; Oki et al., 2003a; Arnell, 2004b). Climate change is only one factor that influences future water stress, while demographic, socio-economic, and technological changes may play a more important role in most time horizons and regions. In the 2050s, differences in the population projections of the four SRES scenarios would have a greater impact on the number of people living in water-stressed river basins (defined as basins with per capita water resources of less than 1,000 m^3/year) than the differences in the emissions scenarios (Arnell, 2004b). The number of people living in severely stressed river basins would increase significantly (Table 3.2). The population at risk of increasing water stress for the full range of SRES scenarios is projected to be: 0.4 to 1.7 billion, 1.0 to 2.0 billion, and 1.1 to 3.2 billion, in the 2020s, 2050s, and 2080s, respectively (Arnell, 2004b). In the 2050s (SRES A2 scenario), 262-983 million people would move into the water-stressed category (Arnell, 2004b). However, using the per capita water availability indicator, climate change would appear to reduce global water stress. This is because increases in runoff are heavily concentrated in the most populous parts of the world, mainly in East and South-East Asia, and mainly occur during high flow seasons (Arnell, 2004b). Therefore, they may not alleviate dry season problems if the extra water is not stored and would not ease water stress in other regions of the world.

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 (income, water-use efficiency, water productivity, industrial production) increases (Alcamo et al., 2007). Income growth has a much larger impact than population growth on increasing water use and water stress (expressed as the water withdrawal-to-water resources ratio). Water stress is modelled to decrease by the 2050s on 20 to 29% of the global land area (considering two climate models and the SRES A2 and B2 scenarios) and to increase on 62 to 76% of the global land area. The principal cause of decreasing water stress is the greater availability of water due to increased precipitation, while the principal cause of increasing water stress is growing water withdrawals. Growth of domestic water use as stimulated by income growth was found to be dominant (Alcamo et al., 2007).

The change in the number of people under high water stress after the 2050s greatly depends on emissions scenario: substantial increase is projected for the A2 scenario; the speed of increase will be slower for the A1 and B1 emissions scenarios because of the global increase of renewable freshwater resources and the slight decrease in population (Oki and Kanae, 2006). Nevertheless, changes in seasonal patterns and the increasing probability of extreme events may offset these effects.

Table 3.2. *Impact of population growth and climate change on the number of people (in millions) living in water-stressed river basins (defined as per capita renewable water resources of less than 1,000 m^3/yr) around 2050 (Arnell, 2004b; Alcamo et al., 2007).*

	Estimated millions of people	
	From Arnell, 2004b	From Alcamo et al., 2007
Baseline (1995)	1,368	1,601
2050: A2 emissions scenario	4,351 to 5,747	6,432 to 6,920
2050: B2 emissions scenario	2,766 to 3,958	4,909 to 5,166

Estimates are based on emissions scenarios for several climate model runs. The range is due to the various climate models and model runs that were used to translate emissions scenarios into climate scenarios.

Box 3.1. Costs of climate change in Okanagan, Canada

The Okanagan region in British Columbia, Canada, is a semi-arid watershed of 8,200 km^2 area. The region's water resources will be unable to support an increase in demand due to projected climate change and population growth, so a broad portfolio of adaptive measures will be needed (Cohen and Neale, 2006; Cohen et al., 2006). Irrigation accounts for 78% of the total basin licensed water allocation.

Figure 3.7 illustrates, from a suite of six GCM scenarios, the worst-case and least-impact scenario changes in annual water supply and crop water demand for Trout Creek compared with a drought supply threshold of 30 million m^3/yr (36% of average annual present-day flow) and observed maximum demand of 10 million m^3/yr (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 emissions scenario in which, 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 the B2 emissions scenario due to higher crop water demands in the warmer A2 world.

Table 3.3 illustrates the range of costs of adaptive measures currently available in the region, that could either decrease water demand or increase water supply. These costs are expressed by comparison with the least-cost option, irrigation scheduling on large holdings, which is equivalent to US\$0.35/m^3 (at 2006 prices) of supplied water. The most expensive options per unit of water saved or stored are metering and lake pumping to higher elevations. However, water treatment requirements will lead to additional costs for new supply options (Hrasko and McNeill, 2006). No single option is expected to be sufficient on its own.

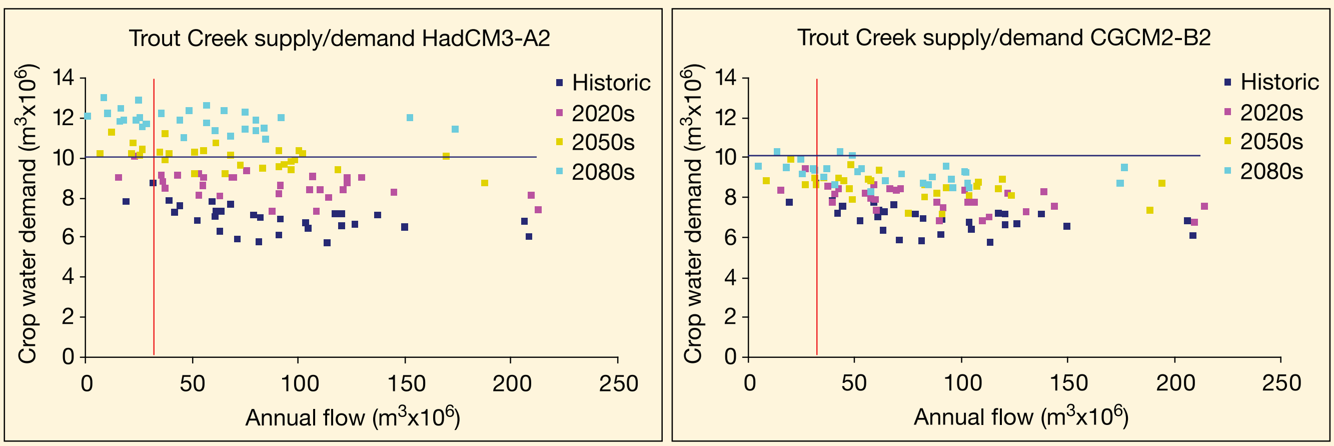

Figure 3.7. *Annual crop water demand and water supply for Trout Creek, Okanagan region, Canada, modelled for 1961 to 1990 (historic) and three 30-year time slices in the future. Each dot represents one year. Drought supply threshold is represented by the vertical line, maximum observed demand is shown as the horizontal line (Neilsen et al., 2004).*

Table 3.3. *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 to 1.7	10%
Public education	Large and medium communities	1.7	10%
Storage	Low to high cost	1.2 to 3.0	Limited (most sites already developed)
Lake pumping	Low (no balancing reservoirs) to high cost (with balancing reservoirs)	1.3 to 5.4	0 to 100%
Trickle irrigation	High to medium demand areas	3.0 to 3.3	30%
Leak detection	Average cost	3.1	10 to 15%
Metering	Low to high cost	3.8 to 5.4	20 to 30%

3.5.2 How will climate change affect flood damages?

Future flood damages will depend heavily on settlement patterns, land-use decisions, the quality of flood forecasting, warning and response systems, and the value of structures and other property located in vulnerable areas (Mileti, 1999; Pielke and Downton, 2000; Changnon, 2005), as well as on climatic changes per se (Schiermeier, 2006). Choi and Fisher (2003) estimated the expected change in flood damages for selected USA regions under two climate-change scenarios in which mean annual precipitation increased by 13.5% and 21.5%, respectively, with the standard deviation of annual precipitation either remaining unchanged or increasing proportionally. They used a structural econometric (regression) model based on time series of flood damage, and population, wealth indicator, and annual precipitation as predictors. They found that the mean and standard deviation of flood damage are projected to increase by more than 140% if the mean and standard deviation of annual precipitation increase by 13.5%. The estimates suggest that flood losses are related to exposure because the explanatory power of population and wealth is 82%, while adding precipitation increases the explanatory power to 89%. Another study examined the potential flood damage impacts of changes in extreme precipitation events using the Canadian Climate Centre model and the IS92a emissions scenario for the metropolitan Boston area in the north-eastern USA (Kirshen et al., 2005b). They found that, without adaptation investments, both the number of properties damaged by floods and the overall cost of flood damage would double by 2100 relative to what might be expected with no climate change, and that flood-related transportation delays would become an increasingly significant nuisance over the course of the century. The study concluded that the likely economic magnitude of these damages is sufficiently high to justify large expenditures on adaptation strategies such as universal flood-proofing for all flood plains.

This finding is supported by a scenario study of the damage due to river and coastal flooding in England and Wales in the 2080s (Hall et al., 2005), which combined four emissions scenarios with four scenarios of socio-economic change in an SRES-like framework. In all scenarios, flood damages are predicted to increase unless current flood management policies, practices and infrastructure are changed. For a 2°C temperature increase in a B1-type world, by the 2080s annual damage is estimated to be £5 billion 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 an A1-type world, with a temperature increase of 2°C, the annual damage would amount to £15 billion by the 2050s and £21 billion by the 2080s (Hall et al., 2005; Evans et al., 2004).

The impact of climate change on flood damages can be estimated from modelled changes in the recurrence interval of present-day 20- or 100-year floods, and estimates of the damages of present-day floods as determined from stage-discharge relations (between gauge height (stage) and volume of water per unit of time (discharge)), 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 four to ten under conditions of doubled atmospheric CO_2 concentrations (Schreider et al., 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 at the core of water management. Historically, water management has concentrated on meeting the increasing demand 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. This assumption is no longer valid. The current procedures for designing water-related infrastructures therefore have to be revised. Otherwise, systems would be over- or under-designed, resulting in either excessive costs or poor performance.

Changing to meet altered conditions and new ways of managing water are autonomous adaptations which are not deliberately designed to adjust with climate change. Drought-related stresses, flood events, water quality problems, and growing water demands are creating the impetus for both infrastructure investment and institutional changes in many parts of the world (e.g., Wilhite, 2000; Faruqui et al., 2001; Giansante et al., 2002; Galaz, 2005). On the other hand, planned adaptations take climate change specifically into account. In doing so, water planners need to recognise that it is not possible to resolve all uncertainties, so it would not be wise to base decisions on only one, or a few, climate model scenarios. Rather, making use of probabilistic assessments of future hydrological changes may allow planners to better evaluate risks and response options (Tebaldi et al., 2004, 2005, 2006; Dettinger, 2005).

Integrated Water Resources Management should be an instrument to explore adaptation measures to climate change, but so far is in its infancy. 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, protecting and restoring natural systems, and including consideration of climate change. In addition, integrated strategies explicitly address impediments to the flow of information. A fully integrated approach is not always needed but, rather, the appropriate scale for integration will depend on the extent to which it facilitates effective action in response to specific needs (Moench et al., 2003). In particular, an integrated approach to water management could help to resolve conflicts among competing water users. In several places in the western USA, water managers and various interest groups have been experimenting with methods to promote consensus-based decision making. These efforts include local watershed initiatives and state-led or federally-sponsored efforts to incorporate stakeholder involvement in planning processes (e.g., US Department of the Interior, 2005). Such initiatives can facilitate negotiations among competing interests to achieve mutually satisfactory problem-solving that considers a wide range of factors. In the case of large watersheds, such as the Colorado River Basin, these factors cross several time- and space-scales (Table 3.4).

Lately, some initiatives such as the Dialogue on Water and Climate (DWC) (see Box 3.2) have been launched in order to raise awareness of climate change adaptation in the water sector. The main conclusion out of the DWC initiative is that the dialogue model provides an important mechanism for developing adaptation strategies with stakeholders (Kabat and van Schaik, 2003).

3.6.2 Adaptation options in principle

The TAR drew a distinction between 'supply-side' and 'demand-side' adaptation options, which are applicable to a range of systems. Table 3.5 summarises some adaptation options for water resources, designed to ensure supplies during average and drought conditions.

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,

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 in the water sector. The DWC initiated eighteen 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, South-east 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 substantial 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 under way. 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.

Table 3.4. *Cross-scale issues in the integrated water management of the Colorado River Basin (Pulwarty and Melis, 2001).*

Temporal scale	Issue
Indeterminate	Flow necessary to protect endangered species
Long-term	Inter-basin allocation and allocation among basin states
Decadal	Upper basin delivery obligation
Year	Lake Powell fill obligations to achieve equalisation with Lake Mead storage
Seasonal	Peak heating and cooling months
Daily to 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

Table 3.5. *Some adaptation options for water supply and demand (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 changing the cropping calendar, crop mix, irrigation method, and area planted
Desalination of sea water	Reduction in water demand for irrigation by importing agricultural products, i.e., virtual water
Expansion of rain-water storage	Promotion of indigenous practices for sustainable water use
Removal of invasive non-native vegetation from riparian areas	Expanded use of water markets to reallocate water to highly valued uses
Water transfer	Expanded use of economic incentives including metering and pricing to encourage water conservation

however, supply-side options, involving increases in storage capacity or abstraction from water courses, tend to have adverse environmental consequences (which can in many cases be alleviated). Conversely, the practical effectiveness of some 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 large volumes of water, use large amounts of energy and may be inconsistent with mitigation policy. Decreasing water demand in a country by importing virtual water (Allan, 1998; Oki et al., 2003b), in particular in the form of agricultural products, may be an adaptation option only under certain economic and social conditions (e.g., financial means to pay for imports, alternative income possibilities for farmers).

These do not exhaust the range of possibilities. Information, including basic geophysical, hydrometeorological, and environmental data as well as information about social, cultural and economic values and ecosystem needs, is also critically important for effective adaptation. Programmes to collect these data, and use them for effective monitoring and early warning systems, would constitute an important first step for adaptation.

In the western USA, water-market transactions and other negotiated transfers of water 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 et al., 2003; Brookshire et al., 2004; Colby et al., 2004). Water markets have also developed in Chile (Bauer, 2004), Australia (Bjornlund, 2004), and parts of Canada (Horbulyk, 2006), and some types of informal and often unregulated water marketing occur in the Middle East, southern Asia and North Africa (Faruqui et al., 2001). Countries and sub-national jurisdictions differ considerably in the extent to which their laws, administrative procedures, and documentation of water rights facilitate market-based water transfers, while protecting other water users and environmental values (Miller, 2000; Faruqui et al., 2001; Bauer, 2004; Matthews, 2004; Howe, 2005). Where feasible, short-term transfers can 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 the 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% of the valley's farm land at Metropolitan's request, thereby creating a water supply of up to 137 Mm^3 for Metropolitan. In exchange, landowners receive a one-time payment per hectare allocated, and additional annual payments for each hectare not irrigated under the programme in that year. The contract also provides funding for community improvement programmes (Miller and Yates, 2006).

Options to counteract an increasing risk of floods can be divided into two categories: either modify the floodwater, for example, via a 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 ability to live with floods (Kundzewicz and 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 Adaptation options in practice

Since the TAR, a number of studies have explicitly examined adaptation in real water management systems. Some have sought to identify the need for adaptation in specific catchments or water-management systems, without explicitly considering what adaptation options would be feasible. 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 USA 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 number of studies have explored the physical feasibility and effectiveness of specific adaptation options in specific circumstances. For example, improved seasonal forecasting was shown to offset the effects of climate change on hydropower generation from Folsom Lake, California (Yao and Georgakakos, 2001). In contrast, none of the adaptation options explored in the Columbia River basin in the USA continued to meet all current demands (Payne et al., 2004), and the balance between maintaining power production and maintaining instream flows for fish would have to be renegotiated. Similarly, a study of the Sacramento-San Joaquin basin, California, concluded that "maintaining status quo system performance in the future would not be possible", without changes in demands or expectations (VanRheenen et al., 2004). A review of the implications of climate change for water management in California as a whole (Tanaka et al., 2006) concluded that California's water supply system appears physically capable of adapting to significant changes in climate and population, but that adaptation would be costly, entail significant transfers of water among users, and require some adoption of new technologies. The feasibility of specific adaptation options varies with context: a study of water pricing in the Okanagan catchment in Canada, for example, showed differences in likely success between residential and agricultural areas (Shepherd et al., 2006).

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 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 and 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 and the water management system as a whole 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, ineffective water governance and uncertainty over future climate change impacts constrain the ability of organisations to adapt to changes in water supply and flood risk (Ivey et al., 2004; Naess et al., 2005; Crabbe and Robin, 2006).

These factors together influence the adaptive capacity of water-management systems as well as other determinants such as sensitivities to change, internal characteristics of the system (e.g., education and access to knowledge) and external conditions such as the role of regulation or the market.

3.6.5 Uncertainty and risk: decision-making under uncertainty

Climate change poses a major conceptual challenge to water managers, in addition to the challenges caused by population and land-use change. It is no longer appropriate to assume that past hydrological conditions will continue into the future (the traditional assumption) and, due to climate change uncertainty, managers can no longer have confidence in single projections of the future. It will also be difficult to detect a clear climate-change effect within the next couple of decades, even with an underlying trend (Wilby, 2006). 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 among scenarios, although temperature-based impacts, such as changes in the timing and volume of ice-melt-related streamflows, tend to be more robust (Maurer and 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 and 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; Nawaz and Adeloye, 2006): 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 (e.g., Wilby and Harris, 2006), although the resulting probability distributions will be influenced by the assumed initial probability distributions. Jones and 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, the UK, and the 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). Measures to cope with the increase of the design discharge for the Rhine in the Netherlands from 15,000 to 16,000 m^3/s must be implemented by 2015, and it is planned to increase the design discharge to 18,000 m^3/s in the longer term, due to climate change (Klijn et al., 2001). 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 and Delaney, 2006). This procedure basically involved the companies estimating when climate change might impact upon the reliability of supply and, depending on the implementation of different actions, 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 whether to invoke contingency plans to add temporary supplies or to tighten restrictions on water use.

A rather different way of coping with the uncertainty associated with estimates of future climate change is to adopt management measures that are robust to uncertainty (Stakhiv, 1998). 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; Olsen, 2006).

3.7 Conclusions: implications for sustainable development

Most of the seven Millennium Development Goals (MDGs) are related directly or indirectly to water management and climate change, although climate change is not directly addressed in the MDGs. Some major concerns are presented in Table 3.6 (UNDP, 2006).

In many regions of the globe, climate change impacts on freshwater resources may affect sustainable development and put at risk, for example, the reduction of poverty and child mortality. Even with optimal water management, it is very likely that negative impacts on sustainable development cannot be avoided. Figure 3.8 shows some key cases around the world where freshwater-related climate change impacts are a threat to the sustainable development of the affected regions.

'Sustainable' water resources management is generally sought to be achieved by Integrated Water Resources Management. However, the precise interpretation of this term varies considerably. All definitions broadly include the concept of maintaining and enhancing the environment, and in particular the water environment, taking into account competing users, instream ecosystems, and wetlands. Also, wider environmental implications of water management policies, such as implications for land management, or the implications of land management policies for the water environment, are considered. Water and land governance are important components of managing water in order to achieve sustainable water resources for a range of political, socio-economic and administrative systems (GWP, 2002; Eakin and Lemos, 2006).

Energy, equity, health, and water governance are key issues when linking climate change and sustainable development. However, few studies on sustainability have explicitly incorporated the issue of climate change (Kashyap, 2004). Some studies have taken into account the carbon footprint attributable to the water sector. For example, desalination can be regarded as a sustainable water management measure if solar energy is used. Many water management actions and adaptations, particularly those involving pumping or treating water, are very energy-

Table 3.6. *Potential contribution of the water sector to attain the MDGs.*

Goals	Direct relation to water	Indirect relation to water
Goal 1: Eradicate extreme poverty and hunger	Water as a 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 improves local-level sustainable development Reduced urban hunger by means of cheaper food from more reliable water supplies
Goal 2: Achieve universal education		Improved school attendance through improved health and reduced water-carrying burdens, especially for girls
Goal 3: Promote gender equity and empower women	Development of gender sensitive water management programmes	Reduce time wasted and health burdens from improved water service leading 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 better quality, and improved sanitation reduce 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 recycles 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 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

intensive. Their implementation would affect energy-related greenhouse gas emissions, and energy policy could affect their implementation (Mata and Budhooram, 2007). 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).

Mitigation measures that reduce greenhouse gas emissions lessen the impacts of climate change on water resources. The number of people exposed to floods or water shortage and potentially affected is scenario-dependent. For example, stabilisation at 550 ppm (resulting in a temperature increase relative to pre-industrial levels of nearly 2°C) only reduces the number of people adversely affected by climate change by 30-50% (Arnell, 2006).

3.8 Key uncertainties and research priorities

There are major uncertainties in quantitative projections of changes in hydrological characteristics for a drainage basin. Precipitation, a principal input signal to water systems, is not reliably simulated in present climate models. However, it is well established that precipitation variability increases due to climate change, and projections of future temperatures, which affect snowmelt, are more consistent, such that useful conclusions are possible for snow-dominated basins.

Uncertainty 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 completed so far, it is difficult to assess in a reliable way the 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 are already considering explicitly how to incorporate the potential effects of climate change into policies and specific designs.

Research into the water–climate interface is required:

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

Among the research issues related to the climate–water interface, developments are needed in the following.

- It is necessary to improve the understanding of sources of uncertainty in order to improve the credibility of projections.
- There is a scale mismatch between the large-scale climatic models and the catchment scale, which needs further resolution. Water is managed at the catchment scale and adaptation is local, while global climate models work on large spatial grids. Increasing the resolution of adequately validated regional climate models and statistical downscaling

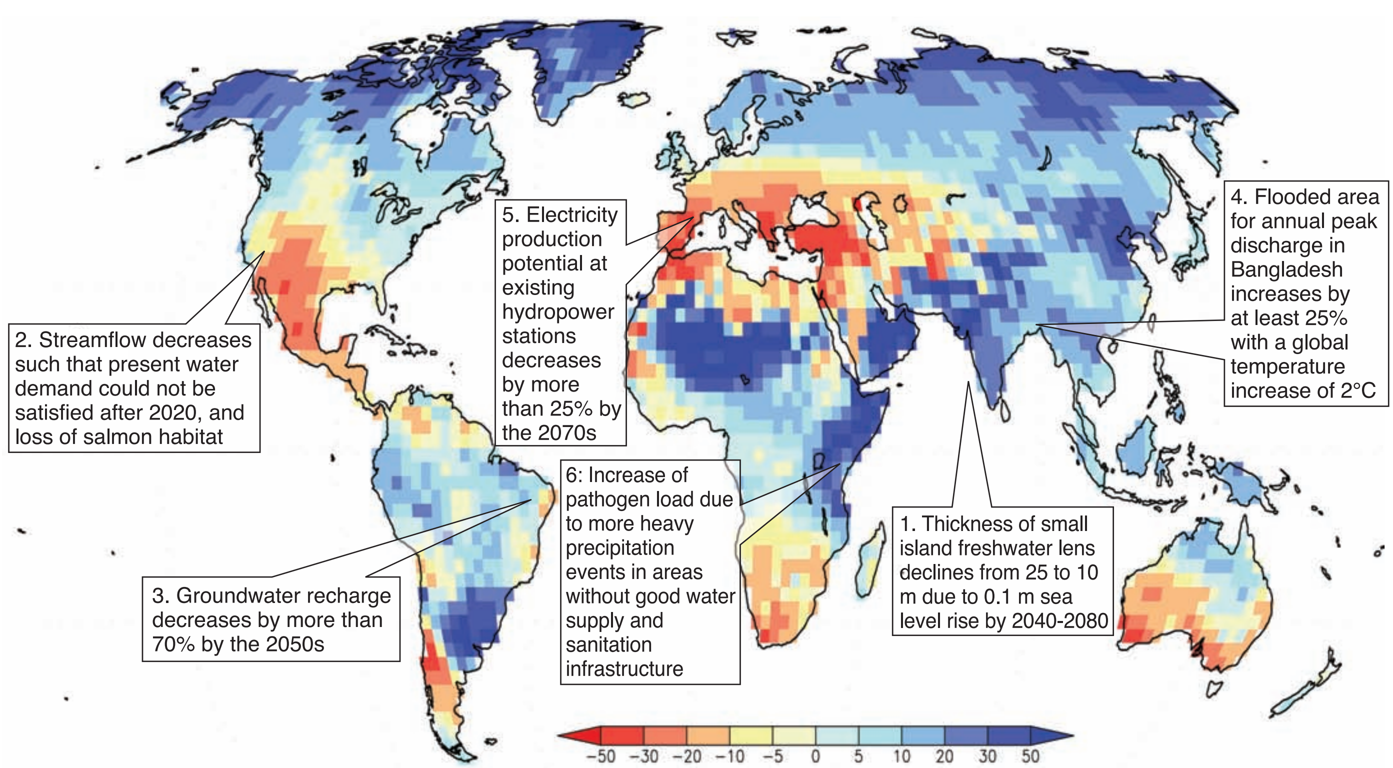

Figure 3.8. *Illustrative map of future climate change impacts on freshwater which are a threat to the sustainable development of the affected regions. 1: Bobba et al. (2000), 2: Barnett et al. (2004), 3: Döll and Flörke (2005), 4: Mirza et al. (2003) 5: Lehner et al. (2005a) 6: Kistemann et al. (2002). Background map: Ensemble mean change of annual runoff, in percent, between present (1981 to 2000) and 2081 to 2100 for the SRES A1B emissions scenario (after Nohara et al., 2006).*

can produce information of more relevance to water management.

- Impacts of changes in climate variability need to be integrated into impact modelling efforts.
- Improvements in coupling 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 in this area, with particular reference to the impacts of extreme events, and covering the needs of both developed and developing countries.
- Relatively few results are available on the economic aspects of climate change impacts and adaptation options related to water resources, which are of great practical importance.
- Research into human-dimension indicators of climate change impacts on freshwater is in its infancy and vigorous expansion 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 observed changes in freshwater resources, with particular reference to characteristics of extremes, is a challenging research priority, and methods for attribution of causes of changes in water systems need refinement.
- There are challenges and opportunities posed by the advent of probabilistic climate change scenarios for water resources management.
- Despite its significance, groundwater has received little attention from climate change impact assessments, compared to surface water resources.
- Water resources management clearly impacts on many other policy areas (e.g., energy projections, nature conservation). Hence there is an opportunity to align adaptation measures across different sectors (Holman et al., 2005a, b). There is also a need to identify what additional tools are required to facilitate the appraisal of adaptation options across multiple water-dependent sectors.

Progress in research depends on improvements 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 prerequisite to improving 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. Data on water use, water quality, and sediment transport are even less readily available.

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