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Chapter 3: Freshwater Resources and their Management

Coordinating Lead Authors
Zbigniew W. Kundzewicz (Poland) and Luis Jose Mata (Venezuela)

Lead Authors
Nigel Arnell (UK), Petra Döll (Germany), Pavel Kabat (The Netherlands), Blanca Jimenez (Mexico), Taikan Oki (Japan), Roland Schulze (South Africa), Zekai Sen (Turkey), Igor Shiklomanov (Russia)

Contributing Authors
Jun Asanuma (Japan), Stewart Cohen (Canada), Mark Nearing (USA), Roger Pulwarty (Trinidad and Tobago), Renoj Thayyen (India), Tom Wilbanks (USA)

Review Editors
Alfred Becker (Germany), James Bruce (Canada)

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Executive Summary

The Executive Summary presents seven key emerging findings regarding freshwater resources in relation to current and future sensitivities, trends, impacts of, vulnerability and adaptation to climate change as well as implication for sustainable development.

Climate-driven changes in river flow and other components of the water cycle have already been observed. Even stronger changes are projected. Significant climate-related changes in runoff, evaporation, groundwater, soil water, and snow cover have already been observed in some regions and even stronger changes are projected. Very strong winter climate-related runoff increase (typically between 50 and 70% within the last two decades) has been detected in most pristine Russian rivers.

Floods and droughts have become more severe in some regions are very likely to increase in severity still further. It is well established that precipitation characteristics have changed and will continue to change towards more intense and intermittent spells. This translates into more frequent and more severe water-related extremes (i.e., floods and droughts). In some regions (e.g., England and continental Europe), changes of high river flow detected from long-term gauge records are already statistically significant. More intensive rainfalls accompanied by a warmer climate lead to increase in rainfall flood events, while floods caused by snowmelt and ice-jamming show a downwards trend over some areas. Increase in severity of summer droughts in continental interiors has also been observed and projected. Flood and drought damages depend on the exposed populations, economies and societies and their adaptive capacity.

Water demand is likely to grow due to climate change. Water demand is likely to increase at the global level due to climate change. In some regions, especially those with high demographic growth, the water needs for irrigation will considerably increase while available water resources may decrease. The impact of climate change on water demand is strongly dependent on adaptation but an exacerbation of the conflicts between water uses (municipal, agriculture and industry) may be expected.

Climate change impacts on water quality are likely to be serious. In general, water quality may be degraded through higher water temperatures. Adverse effects of growing severity of water extremes on water quality have been well established. Where flows decrease, water quality is exacerbated. But even if flow increase causes increasing dilution, floods may lead to water quality problems, such as pollutants and sewage flushed by runoff and overflowing sewage treatment plants. Presence of pathogens has been detected in surface water and groundwater after intense rainfalls. This problems will be more severe in developing countries. Sea level rise increases the risk of saltwater intrusion to groundwater, exacerbated by over pumping of fresh groundwater, thus endangering the water supply of many people populating particularly large metropolitan areas located close to the sea.

Climate change is one of multiple pressures on water resources. In many areas and in particular in water-shortage areas, anthropogenic pressures, such as population and economic growth and land-use change, and not climate change, are the decisive factors behind adverse changes in freshwater resources. However, climate change will exacerbate the situation.

Quantitative projections of changes in hydrological characteristics for a drainage basin, the basic unit of water management, are very uncertain. Precipitation, the principal input signal to water systems is not reliably simulated in climate models. This has two implications. First, adaptation procedures need to be developed, which do not rely on precise projections of changes in river discharge, groundwater, etc. Second, based on the studies done so far, it is difficult to assess water-related consequences of climate policies and emission pathways with high reliability.

Integrated water management must be extended to include the effects of climate change Whereas it is difficult to make concrete projections; it is known that hydrological characteristics will change in the future. Therefore in water management, the past can no longer be the key to the future. Integrated water management, necessary for solving increasingly complex water problems, needs to take into account climate change and consider adaptation options. Water managers in some countries (e.g. flood management and water supply management in the UK) are already considering explicitly how to incorporate the potential effects of climate change into policies and specific designs. Evidence so far suggests that climate change affects the decision-making process. Technology is only one of the tools that can help to control the effects of climate change on water quantity and quality. However, other tools in the economic and social domains are necessary, for both developed and developing countries.

3.1 Introduction

This section basically introduces the climate and water issue, the scope of the chapter as well as a summary of the main points presented in the TAR. It also identifies gaps and presents some topics that were insufficiently covered in the TAR.

Climatic system and freshwater system are interconnected in a complex way, so that any change in one of these systems induces a change in another one. Climate change exerts considerable impact on the freshwater resources and their management. This refers to water in all forms (liquid, solid, gaseous), in quantity and quality aspects. Hydrological systems may amplify changes in climate due to non-linearity in response (e.g., runoff response requires threshold to occur) and complexity of structure, inter-relations, and feedbacks. In the present chapter a comprehensive assessment of climate-water links, including impacts, vulnerability, and adaptation is undertaken.

Water is indispensable, in high volumes, to sustain life and, virtually, in every human activity. Access to freshwater is now being regarded as a universal human right and extending access to safe potable water is one of the Millennium Development Goals. However, due to a number of changes in non-climatic factors, such as population increase and rising living standards, the availability of water of appropriate quality is likely to become increasingly restricted. On top of this, climate change is likely to exacerbate water problems in the future.

In the TAR the state of knowledge of climate change impacts on hydrology and water resources was presented in the light of literature up to 2000 inclusive (Arnell and Chunzhen Liu, 2001). Basic understanding of the climate change and implications for hydrological cycle, water resources and their managements were presented with regional and sectoral interpretation. These TAR findings will serve as a starting point for the assessment made in this chapter:

- 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.
- Peak streamflow is likely to move from spring to winter in many areas.
- Glacier retreat is likely to continue, and many small glaciers may disappear.

- Water quality is likely generally to be degraded by higher water temperature, but this may be offset regionally by increased flows.
- Flood magnitude and frequency are likely to increase in most regions, and low flows are likely to decrease in many regions.
- Demand for water generally is increasing as a result of population growth and economic development, but is falling in some countries.
- The impact of climate change in water resources also depend on system characteristics, changing pressures on the system, how the management of the system evolves, and what adaptations to climate change are implemented.
- Climate change challenges existing water resources management practices by adding additional uncertainty.
- Adaptive capacity is distributed very unevenly across the world.

Flash floods in arid and semi-arid regions, climate change impacts on groundwater recharge, erosion, regional changes in storminess, changes in ice regimes in rivers, lakes and reservoirs, including floods caused by ice jams and changes in the permafrost zone in particular were among issues insufficiently tackled in TAR.

Basically, the present chapter will cover the following points

- New scenarios for the future (in particular based on SRES)
- Detection and attribution of changes in characteristics of water resources (Assessment of observed current changes in physically-based and in natural managed systems)
- Improved knowledge about the impacts of climate change on extreme events (floods, droughts), engineering aspects, and management strategies
- Strategic planning of freshwater resources
- New techniques of adaptation to climate change impacts.

3.2 Current sensitivity/vulnerability

This section aims to describe the current degree to which water systems are affected, either adversely or beneficially by climate variability and change. Mostly, the effects analyzed are direct effects such as changes in surface and soil waters, evapotranspiration and groundwater corresponding to changes in the mean, range, or variability of temperature and precipitation. Some indirect effect such as change in the intensity and frequency of floods and droughts are also evaluated. Also the current states of water availability and use as well as quality are analyzed.

Changes in vulnerability, i.e. the degree to which the water systems is susceptible to, or unable to cope with, adverse effects of climate change, including variability and extremes; and adaptation by water management also form part of this section.

Global water cycles are essential in the Earth System; playing the primary role in mass and heat transport, and controlling the biogeochemical cycles. According to the paradigm shift of research in natural sciences, after the wide recognition of global environmental problems, it is the era (“The Anthropocene”) for geosciences to study the real situation of the Earth (Crutzen, 2002) including the various impacts of anthropogenic activities. Water cycle is exposed and vulnerable to human impacts. Land-use/land-cover transforms topographical modification and compression of soil layers, including building cities and agricultural activities, have large impacts on water cycles. Water withdrawals and uptake for irrigation, and municipal and industrial water usages modify water cycle significantly for both quantitative and qualitative aspects. These anthropogenic impacts on surface/subsurface water cycles may have indirect effects on atmospheric circulation and regional climate, for example, deforestation may have caused long-term decrease of precipitation in particular months when large-scale circulation (such as the Asian Monsoon) is not dominant for precipitation but the local boundary condition matters (Kanae *et al.*, 2001).

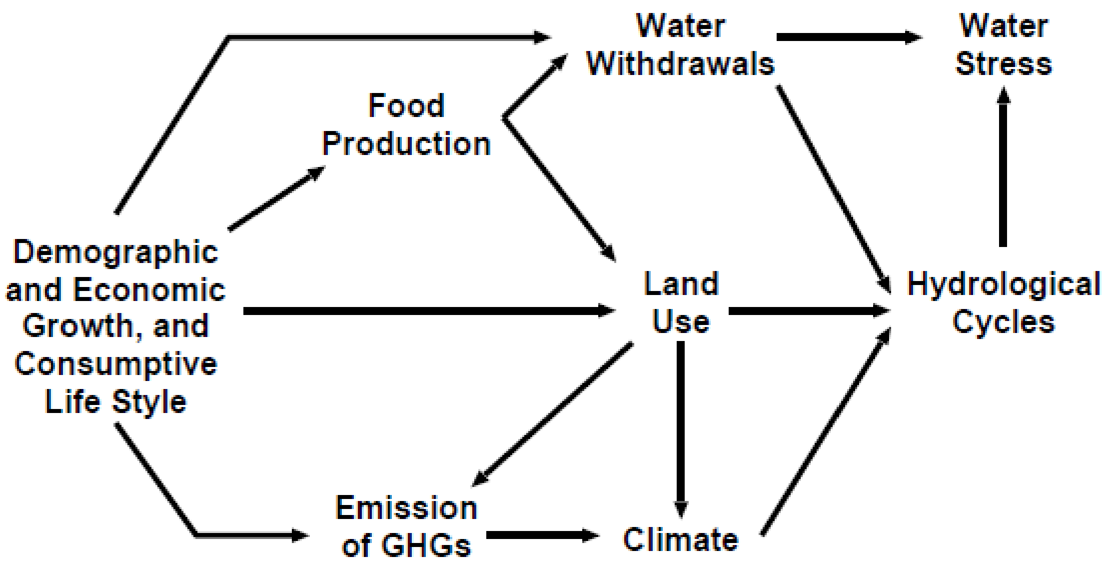


Figure 3.1: *Diagram illustrating major pathways how demographic and economic growth have influence on the changes in hydrological cycles and water resources through changes in land use, water withdrawals, and climate related to food production and the emission of the greenhouse gases (GHGs)*

Figure 3.1 schematically illustrates the impacts of population growth, economic activities, and consumptive life style on hydrological cycle, water withdrawals, and resulting change in water stress (Oki 2005). Water withdrawals increase directly with the growth of population and water usage per capita, and indirectly through the increase in food production. Food production also changes land use, and land use is changed by industrialization, as well. Increased industrial activities and land-use change are increasing the emission of the greenhouse gases (GHGs), and contribute to climate change. Any change in both supply side (hydrological cycle) and demand side (water withdrawals) influences the necessary adaptation in the management of water resources .

Finally, globalization has increased worldwide the transport and trade of “virtual water”. True water transport is the water transport contained in food, beverage, and other industrial products, and it occurs in local, regional, and international scales. The “virtual water” trade is a concept to account the external cost of water consumption; namely, the virtual water content of goods is equal to the amount of water required if the transferred goods are produced in the importing/consuming region or country (Allan 1998; Oki *et al.*, 2003). Even though virtual water trade does not correspond to the amount of physical water transport, the concept is useful to assess the real water scarcity in each region, and is utilized when water resources management issues are concerned (Oki *et al.*, 2004).

3.2.1 Atmospheric and surface waters

This section presents an assessment of changes in surface climate (i.e., changes in precipitation and atmospheric moisture). One of the main conclusion is that patterns of precipitation change are more spatially-variable than the temperature change, but where significant changes do occur they are consistent with measured changes in streamflow. Precipitation over land areas has increased (1901-2003) but there are marked regional differences. They have been increase in the number of heavy precipitation event as well in the so-called rarer precipitation events (1 in 50 year return period).

[Still needs more coordination with WGI findings]

Any change of precipitation in quantity (amount, frequency and intensity), quality, and phase, compared to the current state will cause change in the hydrological cycle and may require adaptation in the water resources management.

Water vapour content in the atmosphere, particularly in its lower part increases with the growth of temperature, even though the significant increase of water vapour contents of the atmosphere has not yet been ubiquitously detected in the observation during the 20th century [reference(s)]. The growth of water vapour contents in the atmosphere increases the potential of precipitation occurrence, and in general, precipitation increases globally, even though the spatial distribution of changes is not uniform (there are both increase and decrease of precipitation over land in low latitudes).

It was not definitively concluded about the change in extreme events of precipitation in the TAR, but the latest studies are suggesting possible increase in extreme events both torrential and scarce precipitation [need to add reference(s)].

The observed trends of precipitation during the 20th century are consistent with above future projections that the global mean precipitation over land has increased but spatial distribution is not as homogenous as temperature rise; some parts of the world, such as Japan, recorded long term decrease in annual precipitation [need to add reference(s) and case(s)].

Even if it is not easy to detect statistically significant trends in extreme precipitation, however, recent studies report that precipitation has become more intense in the late 20th century.

Increase in surface temperature changes surface hydrological cycles in many ways even if precipitation pattern does not change. In some areas, winter precipitation falls frequently as rain rather than snow, snowmelt occurs earlier, and actual evapotranspiration increases [reference(s) needed]. Change of precipitation, more rain and less snow and earlier snowmelt changes the seasonal pattern of river discharge. The peak discharge in spring due to snowmelt decreases and shifts to earlier time, but may not change annual water balance significantly.

Change of annual river discharge is highly influenced by the change in both annual precipitation and annual evapotranspiration. Since there are decadal oscillations of climate system, drawing conclusions from short records, such as a few decadal data, is not rigorous. However, some significant trends were observed during 1961-90 (Oki and Musiake, 1999). Annual river discharge in South-East of North America and South America, such as in Mississippi river basin and Parana river basin, show increasing trends, but decrease is noted in North-West of these continents. There are increasing trends in north-eastern Europe, but decreasing trends prevails in Iberian Peninsula, Africa, and Asia.

Analyses of long-term observation data from hydrological networks of Russia and adjacent countries demonstrate strong changes in annual and seasonal river runoff, streamflow distribution during a year, and ice regimes in water bodies during the last decades. These changes have different trends, depending on the study regime characteristics and on the region.

In most large rivers of Russia (the Volga basin, the rivers of the Arctic Ocean drainage area) an evident annual runoff increase was observed during the last 15-20 years (Shiklomanov & Georgievsky, 2005; Frenkel, 2004; Shiklomanov *et al.*, 2004). The total annual runoff of the six largest rivers of Eurasia discharging to the Arctic Ocean (the Yenisei, Ob, Lena, Kolyma, Severnaya Dvina and Pechora rivers) is characterized by an evident trend towards an increase during 1936-2002 which resembles the tendency towards a rise of the global air temperature and NAO index (Peterson *et al.*, 2002).

The Arctic Ocean received additional 2500 km^3 of water during the last 12 years, including 1500 km^3 from the territory of Russia (Shiklomanov & Shiklomanov, 2003). During 1986-2003, total annual river runoff in Russia increased by 5%, compared with the long-term mean of 1936-1985 (Bedritsky *et al.*, 2004).

No significant long-term change is observed in annual runoff in the Amur river (Novorotsky, 2004). There is a tendency towards annual runoff decrease in the Don and Dnieper rivers (Shiklomanov & Georgievsky, 2005; Vishnevsky & Kosovets, 2004) as well as in the rivers of Transcaucasia and Central Asia (Chub, 2000; Fatullaev, 2004; Makhmudov & Kiazymova, 2004) which may also illustrate an intensive human activity in these basins.

A considerable runoff increase during low-water periods, in winter time in particular, is a common feature of the present changes in water regimes in most of Russia, Ukraine and Belarus (Georgievsky & Shiklomanov, 2003; Shiklomanov & Georgievsky, 2005; Shereshevsky & Sinitskaya, 2004; Shiklomanov *et al.*, 2004; Vishnevsky & Kosovets, 2004; Greben, 2004). Winter runoff increase was observed everywhere during the last 20-25 years and reaches 60-100% of the long-term mean in many regions; being an unusual event with no analogues in the whole observation period of more than a hundred years.

Air temperature rise during the last twenty years in Russia and adjacent countries (most intensive during the cold season (by up to 20C) has resulted in a shorter period of ice coverage (by 4-30 days), ice events and thinner ice cover in large rivers, lakes and reservoirs (Vuglinsky, 2003; Gronskaya & Lemeshko, 2004; Skuratovich *et al.*, 2004; Makagonova, 2004; Vishnevsky & Kosovets, 2004; Ginzburg, 2003, 2005; Shimaraev *et al.*, 2004).

Streamflow is sensitive to the change of human interventions such as water withdrawal for irrigation or other water demands, flow regulation using artificial reservoirs, and land use change. Therefore it is very difficult to evaluate how much change in river discharge can be attributed to the climate change.

3.2.2 Soil water and evapotranspiration

Soil moisture is the water stored in the portion of the soil above the water table. Long-term trend in soil moisture is a good indicator of long-term trend of meteorological conditions at land surface, just like it is the sea-surface temperature over ocean. However, soil moisture observations are not included in the standard set of operational meteorological monitoring network, and soil moisture data are available globally at fewer locations. Data from over 600 stations which include a large variety of global climates showed increasing long term trend in surface top 1m soil moisture content during summer for the stations with the longest records in the United States, countries of the former Soviet Union, and Mongolia (Robock *et al.* 2000)

Since there are not many in-situ observational records and global estimates of remotely-sensed soil moisture data, global soil moisture variations during the 20th century were estimated by an off-line simulation of a land surface model (LSM) as a proxy (Hirabayashi *et al.*, 2005). They prepared atmospheric forcing data necessary to drive MATSIRO, one of LSMs (Takata *et al.*, 2000), from monthly precipitation and maximum and minimum temperature data by New *et al.* (1999), run the LSM for 1901 through 2000, and estimated energy and water balance over global land in 1^o by 1^o longitudinal and latitudinal grids. As seen from Fig. 3.2 of Hirabayashi *et al.* (2005) below, the LSM estimate and in-situ observation corresponds fairly well for the period when observational data is available. However, the decadal variations dominate in the LSM estimates of soil moisture during the whole 20th century, and it is hardly to see any statistically significant long term trend. Further studies are needed in order to verify that there was no long-term trend in the 20th century because the accuracy of LSM estimates highly depend on the forcing data, which can be represented by the density of rain-gauge stations to be used in the preparation of the forcing data (Oki *et al.*, 1999), and the number of rain-gauge data used in the monthly precipitation data by New *et al.* (1999), very limited in the early 20th century.

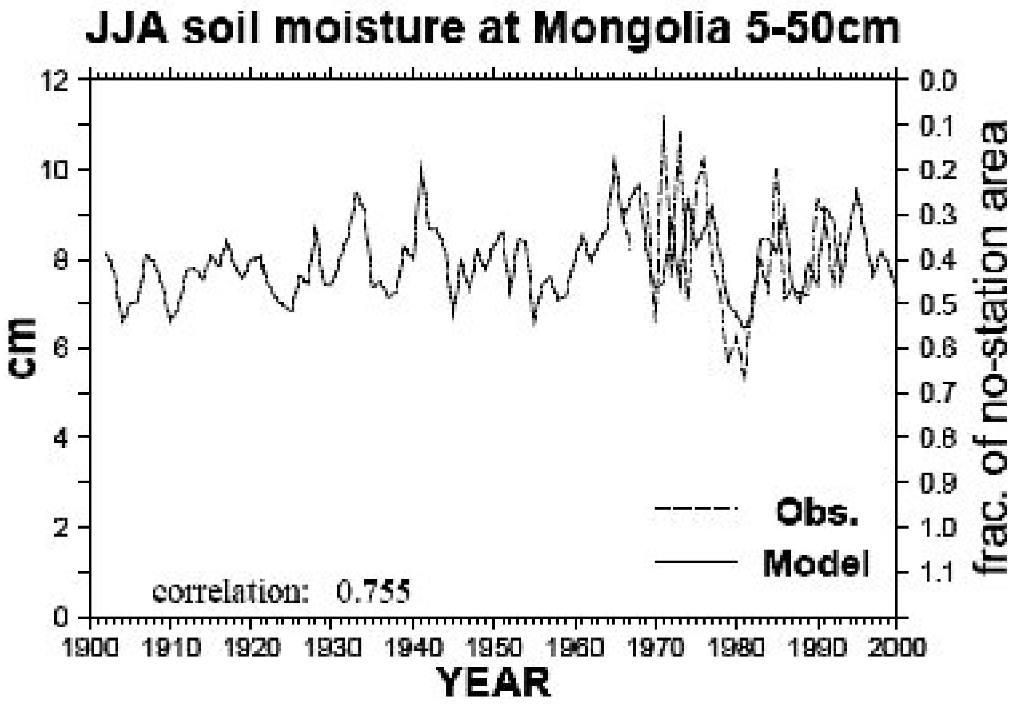


Figure 3.2: *Annual trend of averaged JJA soil moisture in Mongolia. Area average of soil moisture from 5 cm to 50 cm depth of the 100-year simulation (solid line) and station averages of observation (dotted line).*

Since operational measurements of terrestrial evaporation are rarely available, its long-term change and variability have been investigated indirectly, namely using some indices or through the budget approach. It is now a consensus that pan evaporation has been reported to have a decreasing tendencies over the latter half of the 20th century in most of the regions throughout the globe, namely, the conterminous US, Russia (Peterson *et al.*, 1995), India (Chattopadhyay and Hulme, 1997), Thailand (Tebakari *et al.*, 2005), China (Xu, 2001; Liu *et al.*, 2004; Xu *et al.*, 2005), Japan (Asanuma *et al.*, 2004), and Australia (Roderick and Farquhar, 2004), though with noticeable exceptions in several areas. The interpretation of this overall decrease is still controversial. One is through an empirical inverse relationship between pan evaporation and terrestrial evaporation (Brutsaert and Parlange, 1998) concluding that the decreasing trend of the former indicates the increasing trend of the latter (Brutsaert and Parlange, 1998; Lawrimore and Peterson, 2000; Golubev *et al.*, 2001; Hobbins *et al.*, 2004). The other interpretation (Roderick and Farquhar, 2002; Ohmura and Wild, 2002) of the decreasing pan evaporation associates it to the decrease of solar radiation (Stanhill and Cohen, 2001; Cohen *et al.*, 2002; Wild *et al.*, 2005). However, in regions or period without a strong decreasing tendency in the insolation, the decreasing pan evaporation indicates increasing terrestrial evaporation.

The second indirect approach to investigate the long-term variability of the terrestrial evaporation is through the water budget equation of river basins with observations of river runoff and precipitation. Several studies have suggested increasing basin-wide evaporation over conterminous US (Milly and Dunne, 2001; Hobbins *et al.*, 2004; Walter *et al.*, 2004).

Studies of terrestrial or global evaporation using reanalysis data sets (e.g., Serreze *et al.*, 2002) using AGCMs (e.g., Douville *et al.*, 2002; Bosilovich *et al.*, 2005) are already available, though we need few more years to draw reliable conclusions out of them.

3.2.3 Snow and ice

An assessment of the state of glaciers and of the permanent snowpack in the mountains is a good indicator of the global warming on the planet. Numerous studies on the dynamics of mountain glaciers in different regions of the world during the 20^{th} century have been published in the recent years. A rich information is available for regions of North Eurasia and the Himalayas (i.e., the largest mountain system of the Earth). There is a clear tendency towards a considerable decrease of the glaciated areas and glacier mass in most regions during the second half of the 20^{th} century, and in particular during the last decades. During 1953-2001, the Polar Urals lost 55% of its glaciers (Nosenko *et al.*, 2003); during 1960-1977 more than 10 glaciers melted away out of 97 small glaciers fixed in the Byrranga Mountains within the Taimyr Peninsula (Govorukha, 1989).

During 1895-2000, the glaciated area within the Great Caucasus was reduced by 43.2%; the volume of glaciers decreased by 56.1%; the lower boundary of the glaciers rose from 160 m up to 300 m (Panov & Lurie, 2004). Significant reduction of glacier areas and mass in different regions of the Caucasus during the 20th century was reported (Zolotarev *et al.*, 2002; Meier *et al.*, 2003; Nesenko *et al.*, 2003).

In the second half of the last century, the areas and mass of the glaciers reduced from 15% to 32% in Central Asia, in the Tien Shan and Pamir Mountains (Shetinnikov, 1998; Vilesov *et al.*, 2001; Khromova *et al.*, 2003; Meier *et al.*, 2003); while the glaciers in the Altai Mountains lost about 10% of their mass (Asian *et al.*, 2003).

Glacier degradation in the mountains of the Caucasus and Central Asia attained the phase when ice melt does not increase runoff of large rivers. At present, air temperature rise and intensive glacier melt within the river basins with small percentage of glaciated areas have led to reduced glaciation and its smaller contribution to river runoff (Aizen *et al.*, 1997, 2003).

It should be noted that in North Eurasia degradation of glaciers on the Arctic islands of Russia is not so intensive, compared to that in the mountains on the continent. The total glaciated area on these islands (Novaya Zemlya, Severnaya Zemlya, Franz Josef Land) decreased during the second half of the 20th century by 725 km^2 or 1.3% only (Glazovsky, 2003).

Himalayan glaciers are in a general state of recession since mid-18th century (Mayewsky and Jeschke, 1979) and average rate of recession during the last 30 years varied between 2.6 to 28 m/yr (Vohra, 2000; Srivastsva *et al.*, 1999; Kulkarni, 2002). Recession of Himalayan glaciers is independent of their size (Gergan, 2000). Mass balance studies on a selected Himalayan glacier (Dokriani glacier, Ganga Basin, India) demonstrated significant increase in volume of runoff due to glacier degradation in the last decade from 200 mm in 1992 to 455 mm in 1999 (Dobhal *et al.*, 2004; Gergan *et al.*, 2003). This glacier lost 18% of its ice volume during last 33 years (1962-1995).

Intermittent mass balance studies during the last two decades at different areas of Himalayas suggest that the annual average runoff due to glacier degradation along the Himalayan arc varies between 528 mm in the West to 266 mm in the East (Changme Khangpu, Sikkim, India) (Vohra, 2000). Runoff from glacier basins also varies widely across the Himalaya depending on the climatic regime. Siachen glacier, one of the largest (74 km^2) in Karakoram Himalaya produces 1400 mm of summer runoff. This glacier is fed entirely by winter precipitation from western disturbances (Bhutiyani, 1999). Gangotri glacier in monsoon rain shadow region in the central Himalaya produces 2140 mm of summer runoff (Kireet Kumar *et al.*, 2002) whereas Dokriani glacier in the same basin under the monsoon regime produces 3700 mm of average summer specific runoff (Thayyen *et al.*, in press).

The effect of changing climate of the Himalayan region has profound influence on the winter precipitation characteristics. In recent years more of the winter precipitation occurring in the last quarter of the winter season resulting in reduced snow cover area and duration. Himalayan catchments experienced higher annual temperature in 1998, as elsewhere (Thayyen *et al.*, in press) and 1999 experienced lowest winter precipitation in the recent past, which effectively dried up most of the mountain springs in the summer of 1999. Headwater Himalayan rivers are already experiencing climate change related uncertainties triggered by variations in areal distribution of snow and shifting time of occurrence of snowfall in winter months and has major effect on river hydrology, more pronounced than the variations in the volume of runoff due to glacier degradation Recent studies also indicated that the higher mountain regions could experience climatic variations that differ from the lower elevations, suggesting warming of higher mountain regions is possible while meteorological stations at lower elevations indicate cooling (cf. Yao *et al.*, 2000, Shiyin *et al.*, 2003, Thayyen *et al.*, in press).

Air temperature rise and changes in precipitation regime in the monsoon climate are the reasons of glacier degradation. Recent studies also indicated that the higher mountain regions could experience climatic variations that differ from the lower elevations, suggesting that warming of higher mountain regions are possible while meteorological stations at lower elevations indicate cooling (Yao *et al.*, 2000; Shiyin *et al.*, 2003; Thayyen *et al.*, in press). A considerable decrease of glacier mass due to climate warming has been found in Alaska (Arendt *et al.*, 2002), in Patagonia (Rignot *et al.*, 2003), in north-western USA and in Canada (Dyurgerov, 2004). According to (Meier *et al.*, 2003; Dyurgerov, 2004), the most intensive mountain glacier decrease in the world, of the order of 10%, has been observed since the end of 1980.

There is growing evidence that the observed glacier retreat in the warming tropical Andes has accelerated significantly since the early 1980s. For example, glaciers on the Cotopaxi Volcano (Ecuador) lost about 30% of their surface area between 1976 and 1997 (Jordan *et al.*, 2005). The retreat includes relatively large glaciers in the tropics, but it is particularly dramatic for the small-sized glaciers (Francou & Coudrain, 2005). Data suggest that changes in precipitation and cloud cover in the latter portion of the 20th century are minor, and that changes in these quantities are unlikely candidates for explaining Andes glacier retreat (Francou *et al.*, 2003).

A change in the global air temperature has affected the state of the seasonal snow cover, with important consequences for the regions of North Eurasia and northern areas of North America. The present changes in the snow cover are studied by analyzing long-term observed data at meteorological stations (Bulygina *et al.*, 2003; Kitaev *et al.*, 2003; Popova, 2003) and data from satellites (Mognard *et al.*, 2003). The analysis of diurnal data base on snow cover for 100 stations in Russia for the observation period longer than 100 years made it possible to discover specific regional features in variations of mean snow depths for 10-day periods (Bulygina *et al.*, 2003). In the north of the European Russia snow depths tend towards decrease early in winter and towards an increase late in winter. For the whole territory of Russia the number of days with snow depths not exceeding 1 cm tends towards a decrease, whereas the number of days with snow depths exceeding 20 cm tends towards a slight increase. Changes in snow depth depending on the type of atmospheric circulation are analysed for different regions of Russia (Popova, 2003).

3.2.4 Groundwater

Groundwater and climate are linked in many ways. Groundwater systems tend to respond more slowly to variability in climate conditions than do surface water systems [High confidence]. The links between climate and groundwater should receive greater attention as part of climate change and variability studies, groundwater quality analysis, and assessment of the availability and sustainability of groundwater resources. Catchments (e.g. river Meuse) with dominance of the fast runoff component over groundwater base flow are more sensitive to climate change than others (De Wit *et al.*, 2001). A study in the Winnipeg area of Canada, where historical time series of temperature, precipitation and groundwater levels were analyzed (Chen *et al.*, 2004), showed that more than 70% of the variations in the groundwater levels can be explained by variations in the 3-year moving average of annual precipitation, which increased by 6% over 105 years. The higher the mean annual temperature, the stronger is the impact of temperature on groundwater levels. Comparing groundwater levels during a “hotter and drier” period with those during a “cooler and wetter” 4-year period (temperature difference 0.4°C, precipitation 500 mm/a instead of 600 mm/yr), the average drop in groundwater levels was 1.7 m, with a wide range from 1 to 6 m. The impact of climate change on an unconfined aquifer of highly permeable alluvial deposits in southern Canada reveals that the changes in river flows (stages) influence groundwater levels much stronger than changes in groundwater recharge (Allen *et al.* 2004). This is mainly due to the hydraulic connection of river and groundwater, and the relatively low recharge rates in the semi-arid basin. The areas with relatively higher hydrological variability are not necessarily more sensitive to climatic changes. The location of permeable layers (prone to groundwater rise) in relation to rich storages (lower stress) and higher gradients (higher stress) influences the sensitivity of a site with respect to climate changes (Schmidt and Dikau, 2004).

Trends of declining groundwater levels were related to trends of increasing aridity (climate change) (Jorgensen and Al-Tikirity, 2003). The trends of the groundwater isotopic contents with time suggest that although pluvial periods are part of the climatic cycles in the region, there seems to be a significant change in the climatic conditions at the source of the moisture from one pluvial period to the next (Bajjali, and Abu-Jabal, 2002).

As a result of climate change, in many aquifers of the world the spring recharge retreats towards winter with more or less the same rates, but summer recharge declines dramatically [High confidence]. Climate change has impacts on both quantity and quality of groundwater resources. Indirect effects of climate change on groundwater quantity can result from climate-induced changes of groundwater withdrawals or land use. Climate change may lead to vegetation changes, affecting groundwater recharge [Medium confidence]. Changes in any key climatic variables could significantly alter recharge rates for major aquifer systems and thus the sustainable yield of groundwater in the region [High confidence]. For shallow aquifers, temperature has a greater influence on groundwater levels than precipitation. A recent study in southern Manitoba shows that climate trends have good correlations with groundwater level variations (Chen *et al.* 2002). Results suggest that a trend of increasing temperatures, predicted by global climate models for this region, may reduce net recharge and affect groundwater levels (Chen *et al.* 2004) [High confidence]. Yosoff *et al.* (2002) studied the impact of climate change on a chalk aquifer in eastern England and also draw similar conclusions. In summer, mean monthly groundwater recharge and streamflow are reduced by up to 50% potentially leading to problems concerning water quality, groundwater withdrawals and hydropower generation (Eckhardt and Ulbrich, 2003). Rise in temperature and decrease in precipitation lead to a reduction of groundwater recharge (Eitzinger *et al.,* 2003) and groundwater level (Lalikin and Sirodoev, 2004) especially in south-eastern Europe. Study in the Northrhine-Westfalia indicates that in mountainous parts the groundwater recharge change would be smaller than in the plains, where a reduction of up 30% is predicted (Krüger *et al.,* 2002). In the Grand Forks aquifer, located in south-central British Columbia, variations in recharge under the different climate-change scenarios, modelled under steady-state conditions, have a much smaller impact on the groundwater system than changes in river-stage elevation of the Kettle and Granby Rivers, which flow through the valley (Allen, *et al.* 2004).

The quality of groundwater is also affected in many ways by climate change. Warming increases and drought decreases the chances of nitrate pollution to the groundwater, which is often used as a drinking water source (Wessel *et al.* 2004).

Many aquifer regions are very vulnerable to climate change for the three following reasons:
- Large human population may largely depend on the aquifer to meet municipal, agricultural, industrial, and recreational water demands, with limited large-scale alternative water supplies, which are subject to large climatic variability. This relation is stronger in arid and semiarid areas of developing countries (Foster *et al.*, 1998 and 2000 a and b).
- There is a strong linkage between precipitation and groundwater, through the conversion of rainfall to runoff and runoff to aquifer recharge by infiltration and streambed seepage.
- The historical climatic record shows large variability in precipitation and the occurrence of occasional multi-year droughts, which can dramatically reduce natural aquifer recharge (Loaiciga *et al.*, 2000). Climate effects on mean annual groundwater recharge and streamflow are small, as increased atmospheric CO_2 levels reduce stomata conductance thus counteracting increasing potential evapotranspiration induced by the temperature rise and decreasing precipitation (Eckhardt and Ulbrich, 2003) [Medium confidence]

Impacts of climate change on groundwater are well established but incomplete because the relationship between climate variables and groundwater is more complicated than surface water. Groundwater and climate are linked in many ways and groundwater hydrologists need to be more attuned to the effects of climate in the coming decades. Little attention has been directed at determining the possible effects of climate change on shallow aquifers and their interaction with surface water (Alley, 2001).

The potential impacts of climate change on groundwater supplies in the upper carbonate aquifer could include (Chen *et al.*, 2004):

- Less groundwater recharge available due to more evaporative loss of surface water and less precipitation in the winter and spring.
- Longer water residence time due to changes in hydraulic properties in the aquifer especially after prolonged drought.
- Groundwater quality could deteriorate as a result of saline water intrusion if, in response to climate change, fresh groundwater head drops relative to saline waters.

Climate change is very likely to have a strong impact on saltwater intrusion in coastal areas and salinization of groundwater. Relative sea-level rise adversely affects groundwater aquifers and freshwater coastal ecosystems [High confidence]. Rising sea level enhances the intrusion of salt water into coastal aquifers. Other impacts of sea-level rise include changes in salinity distribution in estuaries, altered coastal circulation patterns, destruction of transportation infrastructure in low-lying areas, and increased pressure on coastal levee systems. For two small and flat coral islands off the coast of India, Bobba *et al.* (2000) computed the impact of sea level rise on the thickness of the freshwater lenses. With a sea level rise of only 0.1 m, the thickness of the freshwater lens decreased from 25 m to 10 m for the first island and from 36 to 28 m for the second island. In addition to the sea level rise, any change in groundwater recharge affects the location of the freshwater/saltwater interface, and saltwater intrusion is expected to increase if less groundwater recharge occurs. This can also happen inland where saline water is located next or below freshwater (Chen *et al.*, 2004). For many semi-arid areas, a decrease in precipitation is projected and enhanced evapotranspiration in the warmer world might cause a salinization of groundwater.

3.2.5 Floods, droughts and their impacts

Droughts and floods are natural phenomena. Variables related to water, such as precipitation, river flow and stage, soil moisture or groundwater level, display strong spatial and temporal variability. From time to time these variables take on extremely low or extremely high values, and may exert considerable adverse impacts on the society, and ecosystems.

However, recent extreme hydrological events – droughts and floods – have become more abundant and more destructive than ever in many regions of the globe (Table 3.1). The immediate question emerges as to the extent to which a sensible rise in hazard of droughts and floods can be linked to global changes, and in particular - climate variability and change, in the light of observations made so far.

Table 3.1: *Summary of impact and current vulnerability for some hydrological events [it need to be completed and updated].*

Country or Region, Date	Type of Extreme Event	Hydrological Aspects	Impacts	Current Vulnerability

Prague, Dresden, summer 2002	Flood	Flood peak level exceeded all on record	Above 20 million euros in 2002	low
Siberia, Russia, spring 2001	Ice-jam flood	Very rare frequency (0.5-1%)	Inundation of the Lensk town on the River Lena	medium
North Caucasus	Flood	Due to intense rainfalls in 2002	--	medium
Sahel	Drought	Rainfall below average for over three decades	Natural and human systems	high
Southern Canada	--	Annual minimum daily mean flow has decreased	--	medium

From data compiled by Berz (2001), one may conclude that the number of great flood disasters (those requiring international or inter-regional assistance) in the nine years 1990-1998 was higher than in earlier three-and-half decades, 1950-1985, together. A part of the observed upward trend in weather disaster losses is linked to socio-economic factors, such as increase in population and in wealth gathered in vulnerable areas, and land-use change. However, these factors alone cannot explain the observed growth of the damage and a part of losses is linked to climatic factors. Several destructive floods have recently hit Europe. The material flood damage recorded in the European continent in 2002 was higher than in any single year before (above 20 billion Euro). The 2002 flood peak level of the Vltava in Prague exceeded all the events recorded in the last 175 years (Kubát *et al.*, 2003). The water level of the Elbe in the profile Dresden on 17 August 2002 has considerably exceeded the former highest mark (Becker and Grünewald, 2003), while reconstructed stages are available for more than seven centuries. A notable number of new maximum flow values have been recorded in the last two decades in Scotland. Eight of Scotland's 16 largest rivers (i.e., those with drainage areas over 500 km^2) have been found to have achieved new maximum flows since 1989 (Black and Burns, 2001). Many extreme river floods were observed in Russia and in the NIS during the last years (e. g. Frolov *et al.*, 2005; Dukhovny & Sorokin, 2004). Catastrophic floods of a very rare frequency (0.5-1%) in the Lena river basin (June 2001) due to ice jams (Buzin et. al., 2004) and in the North Caucasus (June 2002) due to intensive rainfalls (Frolov et. al, 2005; Tumanovskaya, 2004) resulted in high number of fatalities and severe material damages. Floods affected more people across the globe (140 million per year on average) than all other natural disasters (WDR, 2003). Among natural disasters, floods are the most reported events in Africa, Asia and Europe (WDR, 2004). In Bangladesh three extreme floods events occurred in 1987, 1988 and 1997, inundating almost 70 % of Bangladesh (Mirza, 2003). In India, on average, floods have affected about 33 million persons between 1953-2000 (Mohapatra and Sigh, 2003). Dramatic floods have also occurred in Nepal (Dixit, 2003).

An increase in the frequency of severe floods (on a monthly scale) in 16 extra-tropical basins worldwide during the 20th century was demonstrated (Milly *et al.,* 2002). The conclusion from examination of long series of monthly river flow data was that seven out of eight 100-year floods occurred in the second (more recent) half of the records. However, results of a study of a set of 199 long time series of annual values of maximum daily discharge do not support the hypothesis of a general, and significant, growth of annual maximum river flows (Kundzewicz *et al.,* 2005). Nevertheless, for 70 European time series it was found that the overall maxima (for the whole

1961–2000 period) occurred more frequently (46 times) in the later sub-period, 1981–2000, than in the earlier sub-period, 1961–1980 (24 times). Lack of upward trends in the occurrence of extreme summer floods on the Elbe and the Oder (Central Europe) and presence of downward trends for winter floods on both rivers were detected (Mudelsee *et al.,* 2003). Greater maximum rain-caused floods have been recently observed in East Siberia (Ivanio, 2004) and in the maritime territory of Russia (Makagonova, 2004); while spring snowmelt flow maxima considerably decreased in many rivers of the Ukraine and Belarus (Vishnevsky & Kosovets, 2004; Greben, 2004).

Summarizing, no general and consistent change is visible in observational records - globally, no uniform increasing trend in flood flows has been detected. Indeed, climate-related changes in flood frequency are complex, depending on the flood-generating mechanism. Significantly more intense precipitation has been already observed in many, but not all areas (***add recent references***), hence magnitudes of rainfall-caused river flood may increase with warming. Flood floods decrease in many regions, where spring snowmelt is the principal flood generation mechanism.

Increases in summer drying have been observed over several areas, resulting from high temperatures, which drive potential evapotranspiration, accompanied by low precipitation over longer time periods. Moreover, generally the decrease in snow pack leads to lower soil moisture and river flows in the summer.

Meteorological drought (prolonged precipitation deficit) is typically the source of hydrological drought (low level of surface waters – rivers, lakes, and groundwater), agricultural drought (low level of soil moisture and its adverse effect on cultivated vegetation) and environmental drought (impacts on ecosystems). A socio-economic drought occurs when the demand for water and water-related economic goods and services (e.g. hydropower, fish, aquaculture, irrigated agriculture, horticulture, and forestry) exceed supply. Certain aspects of water scarcity may be related to socio-economic activities and policy, e. g. in urban areas, both physical scarcity of the resource and inadequate service delivery can lead to water scarcity.

Large-impact droughts have recently occurred in several regions. Droughts may strike large areas (up to sub-continental scale) and, by their nature, they may extend in time for months through years to decades. Of particular importance is the decline in rainfall, and consequently – in soil water, groundwater, lake and river level in the Sahel. The region has not yet recovered from the drought, which started in the late 1960s, and isolated wet years in the 1990s have not been sufficient to balance the long-term deficits (cf. L'Hote, 2002, Ozer *et al.*, 2003).

A combination of drought and some human activities may lead to desertification of vulnerable areas. While droughts and desertification have always been present in Africa, the extended Sahelian drought, combined with demographic pressure, has dramatically accelerated the process of desertification of vulnerable areas whereby soil and bio-productive resources become permanently degraded. There are a variety of clearly identifiable human-induced factors for the Sahel drought (over-cultivation, overgrazing, etc.). Nomadism, the traditional lifestyle in the Sahel, has been replaced by the establishment of permanent settlements with livestock and cultivation programmes, leading to an over-exploitation of water resources (Kundzewicz *et al.*, 2002).

Even in developed countries, an extreme drought may cause considerable environmental, economic and social losses. A severe wide-spread and long-lasting summer drought occurred in Europe in summer of 2003. It resulted from interplay of scarce precipitation and record-high temperatures, exceeding 40^{o}C in several European countries, and beating national records. The heat wave in Southern Europe, accompanied by deficient precipitation, has led to wild fires, problems in water supply and energy production, and crop failures. This may be a proxy of summers in a greenhouse climate, cf. Beniston (2004), Beniston and Diaz (2004), Schär *et al.* (2004), Schär and Jendritzky (2004).

On many rivers, the time series of annual minimum daily flow shows a complex behaviour. Zhang *et al.* (2001) found that annual minimum daily mean flow has decreased in Southern Canada, while it increased in the north (northern British Columbia and Yukon Territory). Douglas *et al.* (2000) found evidence of upward trends in low flows at the larger scale in the US Midwest and at the smaller scale in three smaller regions in the US. A dramatically different interpretation would have been achieved if regional cross-correlation had been ignored – then significant trends would have been found in great many more cases. The analysis of the US river flow data carried out by Lins & Slack (1999) showed that for a 70-year period, 1924-1993, nearly half of analysed time series of annual minimum (daily mean) shows significant trend (34 cases), where 32 trends are increasing and only two are decreasing.

Impacts of floods and droughts can be observed in multiple sectors, such as: agriculture (rain-fed, irrigated), energy (hydropower, cooling), transport (navigation, disruption in rail, road, and air travel), settlements and infrastructure (municipal water supply, waste water, structural safety), health and human well-being (diarrhoea, epidemics, stress) and insurance and financial services (material damage, fatalities, disrupted businesses).

3.2.6 Water availability and use

It is increasingly recognized that "freshwater availability and use" should refer both to humans and to other living organisms, in particular to aquatic ecosystems. Water demand of humans (for water withdrawals and instream water use) and aquatic ecosystems (for instream water use) are considered as competing for their share of the runoff or river discharge. First global-scale estimates of water demands of aquatic ecosystems show that in many mostly semi-arid river basins of the world, the (sustainable) availability of water to humans would be significantly lower if man would honour ecosystem demands (Smakhtin, 2004, environmental flow). Due to human negligence of these demands by withdrawals, river regulations and water pollution, the capacity of freshwater ecosystems to support biodiversity is highly degraded at a global level, with many freshwater species facing rapid population declines or extinction (Revenga, 2000). Of all ecosystems, freshwater ecosystems tend to have the highest proportion of species threatened with extinction (Millennium Ecosystem Assessment, 2005).

Freshwater availability for humans is a function of both (surface and groundwater) runoff generation and the technical water supply infrastructure (reservoirs, pumping wells, water works, distribution networks, etc.). Runoff generation is strongly impacted by climate change, and depending on mainly the storage capacities of the river basin. Changes of the seasonal runoff regime can be as important as changes in the long-term average annual runoff and the inter-annual variability of runoff. Often, water availability is expressed on a per-capita basin or in relation to water use, such that it becomes dependent on demographic and water use developments. Freshwater availability for ecosystems is controlled by river flow variability (Richter, 1997) which depends not only on climate variability and change but also on human water infrastructure and management (in particular reservoir operation and water withdrawals).

Human water use is dominated by irrigation, which causes almost 70% of the global water withdrawals of approximately 3500 km^3/year. The remaining withdrawal volumes are shared almost equally by the sectors: thermal power generation, manufacturing and households (including public and commercial water demands) (WRI, date unknown, data; Vassolo, 2005. Irrigation even accounts for more than 90% of global consumptive water use (Shiklomanov, 2000), consumptive water use being the water volume that evaporates during use and is thus not available for reuse downstream. Irrigation water use is influenced by climate change in two ways: the water requirement of a given irrigated area changes with the climate of the area, and a changing climate might lead, for example, to insufficient rain for rainfed agriculture, such that irrigated areas need to be extended. The sensitivity of household water demand (via garden watering) and industrial water demand is comparably small.

Human water use during the last decades was overwhelmingly driven by non-climatic factors. In most countries of the world except some industrialized countries, per capita water use has increased over the last decades due to increased wealth in general and improved water supply in particular. However, reliable time series on water withdrawals are generally not available. Irrigated area has been extended in most countries of the world even though increased agricultural productivity, e.g. by improved cultivars and more nutrients and pesticides, resulted in a higher crop production per water volume. In the developed countries, the annual growth rate of irrigated areas decreased from 2.9%/yr in the 1970s to 1.2%/year in the 1980s and to 0.2%/year in the 1990s. The respective figures for the developing countries are 2.0%/yr, 1.7%/yr and 1.5%/yr (FAO, 2004). It can be assumed that irrigation water withdrawals increased at approximately the same rates, as technology improvements might be outweighed by intensification. Information on observed climate change impacts on irrigation water withdrawals has not been found.

Currently, socio-economic development and natural ecosystems in many river basins suffer from a lack of water. In global-scale assessments, basins with “severe water stress” are defined either by a per-capita water availability below 1000 m^3/yr (based on long-term average runoff) or a ratio of withdrawals to long-term average annual runoff above 0.4. These basins are located in the Mediterranean region, the Near East, South Asia, Northern China, Australia, the USA and Mexico. The estimates for the population living in such severely stressed basins range from 1.4 billion to 2.1 billion (for approximately 1995). (Oki, 2003; Alcamo, 2003; Vörösmarty, 2000; Arnell, 2004.) Due to the strong population dynamics in most of the severely stressed basins, water stress is very likely to have increased independently of the impact of climate change.

3.2.7 Water quality

Climate change modifies quality directly or indirectly (Scarsbrook *et al.*, 2003). Direct effects include increasing water temperature, inducing salinization caused by ocean level rise, sweeping pollutants with heavy rains or concentrating pollutants through evaporation. Deterioration of water quality produced by higher water withdrawals is an indirect effect. Because water quality is an important parameter for water use and services some aspects have been considered in Chapter 4 (Ecosystems and their services), 5 (Food, Fibre, Forestry and Fisheries), 6 (Coastal and Low-lying areas), 7 (Settlement, Industry and Services), 8 (Human Health) and 9-16 (Regions around the world). But in most of these cases, water quality modification was indirectly addressed, focusing mainly in its effects.

Water quality in different types of water bodies

In lakes and reservoirs climate change effects are mainly due to water temperature changes. These changes can result directly from climate change or indirectly through an increase of thermally polluted discharges as result of higher energy demand for more cooling water. In lakes and reservoirs, oxygen regimes, redox potentials, lake stratification, mixing rates and biota development depend on temperature. Modifications are different in each region and situation. It has been shown that water temperature increase due to climate change has reduced fish population in Lake Tanganyika, East Africa; in a larger proportion than anthropogenic activity or overfishing (O'Reilly *et al.*, 2003). In the Biwa Lake in Japan, temperature of the deeper waters has been rising and the lake bottom water oxygen levels have fallen changing the composition of biota (Kumagai, 2003). Also an increase in salinity and in suspended solids in lakes of the United States has been found (Robarts, et al 2005 and in press). Higher organic matter content, dissolved or suspended (Kabat, 2004), has been related to extreme events or long periods of rainfall in Northern Europe water bodies, although its composition or toxicity have not been yet determined. Experimental studies (Fedorov, 2004), showed that temperature rise caused mercury and methane from water bodies to be released to the atmosphere. It was found for the world largest lake, the Baikal, that due to global warming silicon content decreased by about 30% within the whole water mass (Shimaraev *et al.*, 2004).

In rivers, climate change affects also water temperature but in this case the self-purification capacity can be dramatically modified reducing the amount of oxygen than can be dissolved and used for biodegradation. In the Fraser River in British Columbia (Canada), due to a combination of phenomena related to climate change and water quality, longer sections of the river have reached a temperature over 20^{o}C, which is considered as a threshold for degrading salmon habitat (Morrison *et al.*, 2002). In the Upper Rhone River in France fish communities distribution significantly changed due to temperatures modified by climatic warming Daufresne *et al.* (2003). Fluvial erosion, enhanced by extreme rainfalls, transports sediments (with a varied chemical composition) to water bodies. It was found that due to climate (precipitation) change nitrogen loads from rivers flowing to the Chesapeake and Delaware Bays increased in amounts by up to 50% Chang *et al.* (2001). Climate change was shown to be responsible for higher nutrients (N and P) loads in the streams in the Vantaanjoki catchment (Southern Finland) (Bouraoui *et al.* (2004)). In contrast, a correlation between N fluxes and the climate change was difficult to establish for three upland catchments of Norway and Finland due to other confounding factors (Kaste *et al.*, 2004). In the Pilcomayo basin (Bolivia, Paraguay and Argentina) the ENSO phenomenon was reported to influence strongly annual discharges creating siltation of river bed and pollution with heavy metals from mining districts in Potosí with detrimental effects on fisheries (Smolders *et al*, 2002). Similar results have been found in the Puyango River in Ecuador (Tarras-Waldberg *et al*, 2003). In Scottish rivers an important increase of suspended solids has been reported as a consequence of extreme rainfall values caused by the climate change (Gilvear *et al.*, 2002). An increase observed in salinity in the Schuylkill River at Philadelphia was attributed to the climate change, Interlandi and Crockett (2003). Microbial pollution is also a problem. A relationship between climate and coliforms as well as salinity contents in rivers and bays (receiving water from rivers) has been determined (Pierson *et al.*, 2001, Chigbu, 2004). Increase in pollutants, particularly organic matter, in water bodies used as water supplies probably related with climate changes was found, Rice *et al.*, (2004) and Senhorst (2004).

Aquifer salinization is a problem caused not only by sea level rise. Warmer and drier periods modified groundwater recharge, provoking saline water to intrude into freshwater areas in Manitoba, Canada Chen *et al.* (2004). In a two-year experiment to simulate future conditions on climate change, at three European sites, the impact of night-time warming and early summer drought on nitrogen and carbon fluxes was measured. At the Dutch site an increase of 0.5°C doubled the amount of nitrogen leached to the groundwater. However, no significant changes were observed at the two other sites (Schmidt *et al.*, 2004).

Water quality and extreme events

During floods, it is common to suspend water services for several reasons, and their recovery takes time, frequently leaving the population exposed to severely restricted water quantity and low water quality for all their needs. In a similar way, wastewater services (sewerage, treatment plants and other sanitation facilities) are out of service acting as source of pollution. Chemical pollution can also be released to water during floods as a result of the deterioration of industries or oil pipelines and storage tanks (Ebi *et al.*, 2005). Floods are also associated with the contamination of waters with all kinds of materials. For instance, during the El Salado river flood in 2003, 60,000 tons of solid waste were disseminated all over the city of Santa Fé (Magaña, 2004).

Water quality and human health

The relation between human health and water quality as affected by climate change has been widely discussed. There are many diseases that can be disseminated through water, either by drinking it or by consuming crops that are polluted by irrigation. The presence of pathogens in water supplies have been linked with extreme rainfall (Curriero *et al.*, 2001; Cox *et al.*, 2003; Hunter, 2003; Yarza and Chase, 1999), Yamamoto cited by (Scott *et al.*, 2004) and (Faver *et al.*, 2002). In aquifers, a possible relation between virus and extreme events has been mentioned (Hunter, 2003). Definitely, the most studied effects are those relating heavy rains and the transport of pathogens to water supply, because health effects are observed in the short term, and there is much social pressure on governments to address promptly these problems, particularly in developed countries. On the other hand, water quality effects produced by dry periods have not been adequately studied (Takahashi *et al.,* 2001) and need to be assessed, because less water availability will mean higher pollutant concentration.

Climate change has an effect on water-borne diseases (Patz *et al.*, 2000 and 2001) frequently implying a deterioration of microbial water quality. In 2000, climate change was responsible for approximately 2.4% of worldwide diarrhoea cases as estimated by WHO (2001). Positive associations between diarrhoea reports and temperature and extreme rainfall events have been detected in many Pacific islands (Singh *et al.*, 2001). Cholera has been linked to ENSO events and eutrophication-driven algal blooms (Rodó *et al.*, 2002), it has been suggested that cholera follows weather seasons and correlates with ambient temperature (D'Souza *et al.*, 2004). In Latin America cholera and salmonellosis have been related with ENSO events (ADB, 2002). In Europe drinking water-associated diseases increased after heavy rainfalls (Hunter, 2003; (Miettinen *et al.*, 2001).

Water quality and vulnerable regions

Coasts have around one fourth of the world population but less than 10 % of the renewable water supply (Millennium Ecosystem Assessment, 2004); besides this coastal population is growing faster than elsewhere. Climate change combined with intensive exploitation of groundwater threatens development in coasts because of the reduced water availability. In several parts of the world, saline intrusion is already being provoked by excessive water withdrawals from aquifers and a higher salinization is being produced by sea level rise Klein and Nicholls, 1999; Sherif and Singh, 1999; Peirson *et al.*, 2001; Essink, 2001; Beach, 2002 and (Beuhler, 2003). Water salinization in coasts does not affect only fresh water resources; it also degrades other water bodies (mangroves, estuaries, wetlands, etc) described in another chapter. In the city of Beira in Mozambique, Ruosteenoja *et al.*, 2003 found that it was necessary to extend its 50 km pumping main a further 13 km inland to access fresh water. Salinisation also affects rivers. Extensive areas in the Mary River in Australia have already been affected with recorded rates of saline intrusion greater than 0.5 km/yr (Mulrennan and Woodroffe, 1998), and a similar effect has been observed in the Mississippi River delta (Burkett *et al.*, 2002)

Developed and developing regions
Water quality problems and their effects are different in kind and magnitude in developed and developing countries, mainly form the microbial point of view (Jimenez 2003 and Lipp *et al.*, 2001). These differences will increase with climate change negative effects. In developed countries, waterborne diseases linked with floods and extreme rainfalls are greatly reduced by well maintained water and sanitation services (McMichael *et al.*, 2003) but the opposite occurs in developing countries (Wisner and Adams, 2002). Regretfully, with exception of cholera and salmonella, studies relating climate change with the micro-organisms content in water sources and wastewaters do not always refer to pathogens of interest in developing countries (Scott *et al.*, 2004; Cox *et al.*, 2003; Fayer *et al.,* 2003; Rose *et al.*, 2001; Yamamoto *et al.*, 2000; Yarze and Chase, 1999). Additionally, in developing countries droughts will also induce water quality problems. For instance, water scarcity is one of the reasons to operate water supplies intermittently and with pressure drops low quality water is introduced to the drinking water lines. It is estimated that one third of urban water supplies in Africa, Latin America and the Caribbean, and more than half in Asia, are operating intermittently (WHO/UNICEF, 2000).

3.2.8 Erosion

The consensus of atmospheric scientists is that the hydrologic cycle is becoming more vigorous, with increasing precipitation means and even more so the most intense precipitation [coordinate with WGI]. Rainfall amounts and intensities are the most direct and important factors controlling erosional changes under climate change (Nearing *et al.*, 2005).

Pruski and Nearing (2002a) performed sensitivity analysis to investigate how runoff and erosion by water can be expected to change as a function of changes in the average number of days of precipitation per year and changes in the amount and intensity of the rain that falls on a given day. The Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995) was used to simulate erosion for three locations, three soils, three slopes, four crops, and three rainfall change scenarios. Results indicated that soil erosion is most sensitive to rainfall changes associated with rainfall intensity rather than to rainfall amount alone. Comparisons of the results of the soil loss simulations to published relationships for rainfall erosivity factors in the United States suggested that changing both the number of wet days per year and the amount and intensity of precipitation per day is the most realistic scenario for representing changes in precipitation. Under that scenario, each 1% change in average annual precipitation induced a predicted 2.0% change in runoff and a 1.7% change in erosion, not accounting for the effects of land use changes that may have also occurred (Pruski and Nearing, 2002a). This result is in basic agreement with our assessment of historical measured erosion data based on the relationship between rainfall erosivity and rainfall amounts. Results also indicated that the dominant factor related to the change in erosion rate is the amount and intensity of rain that falls in the storm, rather than the number of days of precipitation in a year (Nearing *et al.*, 2005; Pruski and Nearing, 2002a.

Nearing *et al.* (2005) investigated the response of seven soil erosion models from Europe and the United States to basic precipitation and vegetation related parameters using common data from one humid and one semiarid watershed. Principal results were that erosion was more sensitive to changes in rainfall intensity and amount than to either plant canopy or ground cover, changes in rainfall intensities will have a greater impact on runoff and erosion than simply changes in rainfall amount alone, and changes in ground cover have a greater impact on both erosion than changes in canopy cover alone. The similarities in the responses of the disparate models to the basic factors studied gives credibility to the use of erosion models for studying climate change impacts on soil erosion. Given the types of precipitation changes that have occurred over the last century, and the expectations regarding changes over the next century, the results suggested that there is a significant potential for climate change to increase global soil erosion rates unless offsetting conservation measures are taken.

After rainfall change, the second dominant pathway of influence by climate change on erosion rates is through changes in plant biomass. The mechanisms by which climate changes affect biomass, and by which biomass changes impact runoff and erosion are complex (Pruski and Nearing, 2002b) For example, anthropogenic increases in atmospheric carbon dioxide concentrations can cause increases in plant production rates and changes in plant transpiration rates (Rosenzweig and Hillel, 1998), which translate to an increase in surface canopy and ground cover. However, more precipitation may also lead to an increase in biomass production, and increases in soil and air temperature and moisture can cause faster rates of residue decomposition due to increases in microbial activity. Higher temperatures may translate to higher evaporation rates, while more rainfall would tend to lead to higher soil moisture levels. Antecedent soil moisture at the beginning of a storm event affects both the runoff potential and soil susceptibility to erosion. Temperature changes also affect biomass production levels and rates in complex ways. Corn biomass production may increase with increasing temperature, particularly if the growing season is extended, but then may decrease because of temperature stresses as the temperature becomes too high (Rosenzweig and Hillel, 1998). Biomass changes impact soil surface cover, which greatly impacts erosion.

A third important impact of climate change is associated with the changes from snowfall to rainfall. When decreased snowfall translates to increased rainfall, erosion by storm runoff is liable to increase.

3.2.9 Adaptation by water management

What information do water resources managers need to incorporate to take into account the effect of climate change over the next 10-100 years is an important issue that is being developed.
A distinctive property of the water sector is in the role of adaptation, which has been the backbone of water management throughout centuries and millennia. People have always adapted to the changing conditions of largely climate-controlled water availability and demand.

All levels of government, as well as the private sector and individual stakeholders, are regularly engaged in the water management. Hence, in principle, every individual who uses water is a sort of water manager (e.g., a woman in the village who draws water from a well or collects water from a nearby stream) (Kabat *et al.*, 2003).

Management involves being responsible and accountable for the regulation, control, allocation, distribution and efficient use of existing supplies of water to offstream uses such as for example, irrigation and power cooling. Also it includes the development of new supplies, control of floods and the provision of water for instream uses as for example, navigation and environmental flows (Appleton *et al.*, 2003).

Water resources are one of the highest-priority issues with respect to climate changes in many regions (e.g., see box in page xx) A clean and reliable water supply is critical for domestic use, food and energy production. In many regions, within countries, (e. g., Prairie rivers) decreases in flow volumes and water levels are already happening. Data indicate (add reference here) that a long-term trend of declining flows has already begun. Thus, water supply problems should be carefully considered.

Many of the commonly recommended adaptation options to address climate change in the water resources sector, including water conservation and preparedness for extreme events, are based on strategies for dealing with current variability (coping with climate changes). Structural adaptations, such as dams, weirs and drainage canals, tend to increase the flexibility of management operations, although, these adaptation options generate social and environmental costs.

Then, upgrading existing infrastructure to better deal with future climates may often be preferable to building new structure. Design decisions should focus primarily on extreme events and system thresholds, rather than on changes in the mean conditions. It is also important to see demand management as part of the adaptation strategy (e.g., reducing consumer demands for water through mechanism such as water conservation initiatives).

3.3 Assumptions about future trends

This section describes the driving forces on freshwater systems. In Chapter 2 of the AR4, scenarios of the main drivers of sectors and systems are presented. Here, the focus is on the dominant drivers of freshwater systems during the 21st century, distinguishing climatic and non-climatic mechanisms. The former relates to climate and in particular precipitation changes, while the second mechanism is important for understanding how relevant is the impact of climate change when compared to other drivers.

3.3.1 Climate

[To be coordinated with Chapter 10 WG I findings]: Changes in precipitation have implications for the water resources in a future warmer climate. One of the conclusions regarding precipitation change is that at least it can occur with an 80% probability by the end of the 21st century (Furrer and Tebaldi, 2005) for the case of the A1B scenario for DJF and JJA. An increase of precipitation in the tropics and a decrease in the sub-tropics are expected. There are smaller amplitude decreases of mid-latitude summer precipitation. Intense and heavy episodic rainfall event will be interspersed with relative dry periods, producing greater mid-latitude drying as well as more intense precipitation (see Chapter 10 WG I)

Climate change and variability has received large attention from many researchers. The primary approach to study expected climate change has been used to couple global models (GCMs) with hydrological models. Recently, some studies have coupled regional models (RCMs) with hydrological models to study water resources at a watershed level (Sushama et al, 2005). Six basins analyzed (Fraser, Mackenzie, Yukon, Nelson, Churchil and Mississippi) cover most of the climate regions in North America. The results obtained showed an increase in annual precipitation (2-14%) in all basins except the Mississippi basin.

The effect of climate change and variability on water resource reliability, resilience, and vulnerability in a northern region (i.e., Yorkshire which is a region with severe water resource drought) were examined by modelling changes to weather type frequency, mean rainfall statistics, and potential evapotranspiration. Results indicate future improvements in water resource reliability due to increased winter rainfall but reductions in resource resilience and increased vulnerability to drought. The important result however is that, in general, drought events are expected to be more extensive in both magnitude and duration than severe historical droughts when measured using percentage change in total system vulnerability (Fowler *et al.*, 2003).

Anthropogenic emissions of greenhouse gases lead to an increasingly warmer climate, which, mainly due to increased evaporation of the oceans, results in increasingly higher precipitation at the global scale. Climate models agree that evaporative demand (i.e., potential evapotranspiration) will increase in the future, so that runoff and water resources will decrease unless there is not a sufficient increase in precipitation. While temperatures are expected to increase everywhere, precipitation will increase in some regions and decrease in others. In addition, while temperatures will increase during all seasons of the year, although with somewhat different magnitudes, precipitation may increase in one season and decrease in another. Climate models produce strongly different patterns of climate change. The same emission scenario fed to different climate models may produce strongly differing patterns of climate change. The pattern of precipitation change is more complex than the pattern of temperature change as it is primarily governed by changes in the global atmospheric circulation (caused by the increased heat content of the atmosphere), while changes in temperature are more directly related to the globally homogeneous increase in concentration of greenhouse gases. In the case of precipitation, models disagree in sign of change for several regions. Parameter uncertainty of a climate model leads to a much wider range of computed regional changes in precipitation than those derived by scaling a single ensemble member by different climate sensitivities (Murphy *et al.,* 2004).

The uncertainties of the impact of climate change on water resources have been shown to be mainly due to the uncertain climate inputs (in particular precipitation) and less to the uncertainties of the greenhouse gas emissions (Arnell, 2004; Döll *et al.*, 2003), assumed climate sensitivities (Prudhomme *et al.,* 2003) or the hydrological models themselves (Kaspar, 2003). Thus, a multi-model probabilistic approach rather than using the output of only one climate model is desirable to assess the impact of climate change on water resources. Since the TAR, a considerable number of hydrological impact studies have used multi-model climate input (e.g. Arnell, 2004 at the global scale, and Jasper *et al.,* 2004 at a river basin scale).

Global averages of annual temperature and precipitation changes, as computed by 9 climate models, are estimated as follows Cubasch *et al.* (2001). For the A2 emissions scenario, the temperature response for the 30-year average 2071 to 2100 relative to 1961 to 1990 is +3.0°C with a range of +1.3 to +4.5°C, while for the B2 scenario it amounts to +2.2°C with a range of +0.9 to +3.4°C. The precipitation response is an increase of 3.9% with a range of 1.3 to 6.8%, for A2 and an increase of 3.3% with a range of 1.2 to 6.1% for B2. Both the global annual temperature and precipitation changes increase during the 21st century. The smaller the spatial averaging units, the larger the climate-model dependent differences may become. Scatter plots of changes in seasonal temperature and precipitation for 32 world regions (24 of them for land areas) that show the interpretation of the four IPCC emissions scenarios A1F, A2, B1 and B2 as computed by seven global climate models are now available (Ruosteenoja *et al.,* 2003). In most world regions, predicted temperature changes are significant as compared to the natural 30-year internal variability; the magnitudes of temperature increase depend more on the applied climate model than on the emissions scenario. Predicted precipitation changes by 2010-2039 are in most regions less than the natural 30-year internal variability, the exceptions being high latitude regions throughout the whole year and the monsoon regions in Southern and Eastern Asia during the summer monsoon, where statistically significant precipitation increases may already occur. In many regions and seasons, the precipitation changes as computed by different climate models can be of different sign. However, in general, many semi-arid regions are likely to suffer from decreased precipitation (e.g., Southern Africa, Australia, and the Mediterranean region).

It is very likely that heavy precipitation events will increase over many areas of the globe, and it is likely that summer dryness will rise over most mid-latitude continental interiors (Cubasch *et al.*, 2001). Recent works on changes in precipitation extremes in Europe agree that the intensity of daily precipitation events predominantly increases (Giorgi *et al.*, 2004; Räisänen *et al.*, 2004), even in regions where the mean annual precipitation decreases (Christensen & Christensen, 2003, Kundzewicz *et al.*, 2004). The number of wet days decreases (Giorgi *et al.*, 2004), which leads to longer dry periods except in the winter of West and Central Europe. Increase of the number of days with intense precipitation has been projected in Europe (Kundzewicz *et al.*, 2004).

Changes in climate variability at the annual and decadal scales (e.g. ENSO and NAO/AO) under the impact of climate change are still uncertain, so that it is not clear yet whether, for example, the strong droughts and floods related to ENSO will intensify with climate change. For the time being, the warm (i.e., El Nino) phase of ENSO shows a tendency of being more frequent, long-lasting, and intense.

Most climate change impacts studies for freshwater only consider changes in precipitation and temperature, based on changes in the averages of long-term monthly values as provided by climate models, which, at the global scale, are available at the IPCC Data Distribution Centre (http://ipcc-ddc.cru.uea.ac.uk/). In most studies, to compute future climate variables required as input to the impact models, time series of observed climate values are scaled with these computed changes in climate variables , which may lead to implausible future climate input if observed and modelled climate differ strongly. Changes in inter-annual or daily variability of climate variables are generally not taken into account in hydrological impact studies. **references**

3.3.2 Non-climatic drivers

Freshwater systems are affected by a large variety of non-climatic drivers. Availability of water resources (in both quantity and quality aspects) is influenced by land use, surface water impoundments, groundwater overexploitation, water and waste water treatment, and sea-level rise, to name just the most important factors. Water use is driven by changes in population, food consumption, economy (including water price), technology, lifestyle and society’s views about the value of freshwater ecosystems. It can be expected that the paradigm of Integrated Water Resources Management will be increasingly followed all around the world, so that water as a resource and a habitat will come more into the centre of policy making.

Chapter 2 of this AR4 gives an overview of the future development of non-climatic drivers, including: population, gross domestic product, land cover and sea level, focusing on the IPCC SRES scenarios. Here, assumptions about major freshwater-specific drivers for the 21st century are discussed.

Non-climatic drivers of water resources (quantity and quality aspects)
In developing countries, new surface water dams will be built in the future, even though their number is likely to be small compared to the already existing 45,000 large dams (World Commission on Dams, 2000). In developed countries, the number of dams is very likely to remain stable. The issue of dam decommissioning is increasingly becoming a reality, and a few dams have already been removed in France and the USA Howard, 2000, dam; Takeuchi *et al.*, 1998. Increased

future waste water reuse and desalinization are likely possibilities to increase water supply in semi-arid and arid regions (cf. Ragab, 2002; Abufayed, 2003). The cost of desalination including the water transport, will be declining, hence, desalination will increasingly be an option for water supply of not only coastal towns Zhou, 2005, desalination.

With respect to point-source pollution, wastewater treatment is an important driver of water quality, and an increase of wastewater treatment in both developed and developing countries can be expected to improve in the future. In the EU, for example, more efficient wastewater treatment as required by the Urban Wastewater Directive (http://europa.eu.int/comm/environment/water/water-urbanwaste/index_en.html) will lead to a reduction of point source nutrient input to the rivers. However, organic micro-pollutants (e.g. endocrine substances) are expected to occur in increasing concentrations in surface waters and groundwater. This is because the production and consumption of anthropogenic chemicals is 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, a strong increase in point emissions of nutrients, heavy metals and organic micro-pollutants are expected. In developed countries, diffuse emissions of nutrients and pesticides from agriculture will continue to be an important source of contamination, while these emissions are very likely to increase in developing countries.

Global-scale quantitative scenarios of pollutant emissions focus on nitrogen, and the range of plausible futures is large. The scenarios of the Millennium Ecosystem Assessment expect the global N-fertilizer use to reach between 110 and 140 Mt in 2050 as compared to 90 Mt in 2000 Millennium Ecosystem Assessment, 2005. In three of the four scenarios, total N-load increases at the global scale, while in the TechnoGarden scenario, which is similar to the IPCC SRES scenario B1, there is a reduction of atmospheric N-deposition as compared to today, so that the total N-load to the freshwater system decreases.

Non-climatic drivers of water use

According to a FAO projection of agriculture in developing countries Bruinsma, 2003, the developing countries (with 75% of the global irrigated area) are likely to expand their irrigated area by 20% by 2030 (rate of increase 0.6%/yr), while the cropping intensity of irrigated land will increase from 1.27 to 1.41. Most of this expansion will occur in already water-stressed areas, such as South Asia, Northern China, Near East and North Africa. On average, irrigation water use efficiency (ratio of consumptive water use to water withdrawal) is assumed to increase from 0.38 to 0.42. In all four scenarios of the Millennium Assessment, future extension of irrigated area is assumed to be much smaller than in the FAO projection, with global growth rates between 0 and 0.18%/yr between 1997 and 2050 Millennium Ecosystem Assessment, 2005. The largest increase occurs in the Global Orchestration scenario (which is similar to the IPCC A1 scenario) even though it is the scenario with the smallest population increase, while essentially no change in irrigated area occurs in the Order from Strength scenario (similar to the IPCC A2 scenario), with the largest population increase. After 2050 irrigated area stabilizes or slightly declines in all scenarios except Global Orchestration. Irrigation water use efficiencies are assumed to decline in the Order from Strength scenario and to strongly increase in the Global Orchestration and TechnoGarden scenarios.

Important drivers of domestic and industrial water use are, in addition to population and economic development, the application of water-saving technologies and water pricing, which both will counter the effects of demographic and economic increases. In regions with restricted piped water supply, the projected increases in per capita GDP (Chapter 2) will lead to increased per-capita domestic water use, while in the OECD countries, the impact of water-saving technologies will be dominant. In all four Millennium Assessment scenarios, per-capita domestic water use in 2050 is rather similar in all world regions, around 100 m^3/yr (the European average in 2000), which implies a very strong increase in Sub-Saharan Africa (by a factor of 5, approximately) and smaller increases in other world regions except OECD where per capita domestic water use declines Millennium Ecosystem Assessment, 2005. Discussions of future developments of drivers of irrigation, domestic and industrial water use can be found in Alcamo, 2003; Alcamo, 2000; Seckler, 1998; Vörösmarty, 2000.

3.4 Key future impacts and vulnerabilities

This is the central (core) section of the chapter. Main key vulnerability should be identified. Thresholds and confidence levels should be specified whenever is possible. We should recall that it is about impacts and vulnerabilities in the future (under climate change). The sub-section 3.4.9 will take into account multiple stresses and relationships to cross-cutting themes (e.g., agriculture, virtual water trade, energy, industry, transport, settlements (floods, droughts, climate-related migrations, health, insurance, other). [The nomenclature indicated in chapter 19 (key vulnerability) should be used as well as entries for a matrix to be developed in section 3.7].

3.4.1 Atmospheric and surface waters

Since the Third Assessment Report many studies have been conducted into the potential implications of climate change for river flow. Table 3.2 lists around 70 studies published in the international refereed literature, and many more studies are presented in published and unpublished reports. However, studies still tend to be heavily focused towards Europe and North America. Several of the North American studies (Stewart *et al.*, 2004; Payne *et al.*, 2004; Vanrheenen *et al.*, 2004; Dettinger *et al.*, 2004; Knowles & Cayan, 2004; Christensen *et al.*, 2004) are part of a coordinated suite of projects using consistent scenarios and approaches to estimate changes in runoff in different basins in western North America. Most studies use climate scenarios derived from climate models as inputs to off-line catchment-scale hydrological models. Some studies use arbitrary climate changes (Singh, 2003; Singh & Bengtsson, 2004; Legesse at al., 2003) and a few use scenarios based on equilibrium climate change experiments (Drogue *et al.*, 2004; Pfister *et al.*, 2004) and the inverse modelling of water resources (Cunderlik & Simonovic, 2004). The vast majority use climate scenarios based on IS92a emissions (or a 1% increase in CO_2 concentrations a year). Only a very few recent studies (Arnell *et al.*, 2003; Arnell, 2003a; 2004; Hayhoe *et al.*, 2004; Jasper *et al.*, 2004; Zierl & Bugmann, 2005) have so far used SRES-based scenarios.

Table 3.2: *Published studies between 2001 and 2006 about the effects of climate change on river flows (it needs to be updated!)*

Global		**North America**		**Asia**	
Manabe *et al.* (2004)		Hurd *et al.* (2004)	USA	Tao *et al.* (2005)	China
Arnell (2003)		Gordon & Famiglietti (2004)	USA	Bueh *et al.* (2003)	China
Gerten *et al.* (2004)		Rosenberg *et al.* (2003)	USA	Guo *et al.* (2002)	China
Tao *et al.* (2003)		Roy *et al.* (2001)	Quebec	Yu *et al.* (2002)	Taiwan
Douville *et*		Frei *et al.* (2002)	East Coast	Singh (2003)	W Himalaya

al. (2002)			USA		
Nohara *et al*. (2005)		Chang (2003)	Pennsylvania	Singh & Bengtsson (2004)	W Himalaya
Döll *et al*. (2003)		Knowles & Cayan (2004)	California	Wilk & Hughes (2002)	Southern India
		Cunderlik *et al*. (2004)	Ontario, Canada		
Europe		Barlage *et al*. (2002)	Great Lakes	**Africa**	
Boorman (2003)	Finland/UK/ Belgium/Italy /Greece	Jha *et al*. (2004)	Upper Mississippi	Matondo *et al*. (2004)	Swaziland
Booij (2005)	Meuse	Stone *et al*. (2001)	Missouri	New (2002)	South Africa
Drogue *et al*. (2004)	Luxembourg	Christensen *et al*. (2004)	Colorado	Arnell *et al*. (2003)	Southern Africa
Pfister *et al*. (2004)	Rhine	Simonovic & Li (2004)	Red River, Canada	Legesse at al. (2003)	Ethiopia
Shabalova *et al*. (2003)	Rhine	Morrison *et al*. (2002)	Fraser R, Canada	Tate *et al*. (2004)	Lake Victoria
Zierl & Bugmann (2005)	Alpine	Kim (2005)	Western US	Harrison & Whittington (2002)	Zambezi
Jasper *et al*. (2004)	Alpine	Miller *et al*. (2003)	California	Matondo & Msibi (2001)	Swaziland
Mokhov et al (2002, 2003, 2004) (*)	North Eurasia	Stewart *et al*. (2004)	Western US		
Eckhardt & Ulbrich (2003)	Central Europe	Kim *et al*. (2002)	Western US	**Australia**	
Menzel & Burger (2002)	Elbe	Loukas *et al*. (2002)	British Columbia	Chiew & McMahon (2002)	Australia
Burlando & Rosso (2002)	Arno, Italy	Vanrheenen *et al*. (2004)	Sacramento	Evans & Schreider (2002)	W Australia
van der Linden (2003)	Russian Arctic	Loukas *et al*. (2002)	British Columbia	Herron *et al*. (2002)	NSW Australia
Andreasson *et al*. (2004)	Sweden	Payne *et al*. (2004)	Columbia River		
Graham (2004)	Baltic	Leung *et al*. (2004)	Columbia River	**Latin America**	
Arnell (2004)	UK	Shelton (2001)	Oregon	Seoane *et al*. (2005)	Southern Argentina
Arnell (2003)	UK	Maurer & Duffy (2005)	California		
Pilling &	Wales	Hayhoe *et al*.	California		

Jones (2002)		(2004)			
Lehner *et al.* (2001)	Europe	Dettinger *et al.* (2004)	California		
Nachtnebel & Fuchs (2004)	Austria	Huntington (2003)			
		Miller *et al.* (2003)	California		
		Vanrheenen *et al.* (2004)	Sacramento		
		Cunderlik et al (2004)	Ontario		

Besides scenarios adopted in these studies, also methodologies to estimate the possible impacts of the climate change on river runoff are different among studies. In some studies, runoff is simulated directly by GCMs, in others - bias correction to the simulated runoff is introduced, using current runoff estimates. In some studies, water balance models are used to estimate current runoff, and changes in precipitation, temperature, etc., projected by GCMs are used for perturbing inputs to water balance/hydrologic model to estimate river runoff in the future. Direct usage of GCM runoff is most consistent with the projection of future climate, however, due to the poor accuracy of representation of hydrological cycle by GCMs, bias corrections are frequently applied, particularly for quantitative assessment of water resources. However, the way of bias correction matters significantly for the estimate of available water resources in the future (Oki *et al.*, 2003), and currently there is no agreement on the methodological approach to bias correction. Situation is further complicated if climate change signal (such as changes in precipitation and temperature), is taken from GCM simulation results and control data used for land surface/hydrologic/water balance model are modified. In this case, estimated future change of river runoff could be quantitatively different even using the same GCM result under the same social change scenario since each land surface/hydrologic/water balance model can have different sensitivity to temperature and precipitation. Despite the additional arbitrariness, the methodology is widely used because it is easier to obtain quantitatively better estimates of river runoff for current simulation, and also useful to apply the climate change information to runoff simulations on regional and local scales.

All these issues are due to the imperfect accuracy of the GCM simulation, particularly of river runoff, and inter-model variability and inconsistency have been other issues. Recently, the accuracy of GCM estimates has been improved due to the advance in modelling and simulation with higher resolution, and a new concept of multi-model ensemble has been proposed after TAR. The analysis using the multi-model ensemble is developed for the seasonal forecast has been recently applied to the climate change projections (Giorgi and Mearns 2002; Min *et al.* 2004). Giorgi and Mearns (2002) introduced a weighted multi-model ensemble mean (WEM) using information of the biases of the present climate simulations in order to increase the reliability of projections. Min *et al.* (2004) investigated the future climate change over east Asia using the multi-model ensemble of selected AOGCM based on SRES. Nohara *et al.* (2005) showed that weighted ensemble mean with weight inversely proportional to the correlation coefficient of river discharge between observation and GCM simulation for 20th century performs better than other WEM or normal ensemble. They also estimated the multi-ensemble mean for future projection of climate based on 15 GCM simulations by SRES A1B scenario.

For the AOGCM experiments with SRES A1B, the WEM of the global (land) averaged temperature change for year 2100 is +2.7C (+3.7C) increasing relative to the present (defined as average from 1981 to 2000). The land warms faster than the ocean, and there is greater relative warming at high latitudes. The change of the surface temperature directly interacts with the change of the precipitation. Figure 3.3 illustrates WEM of the change of the annual mean precipitation in the future (defined as average from 2081 to 2100) against the present. The precipitation over the land increases in high latitudes, southern to eastern Asia, and central Africa, and decreases in Mediterranean region, southern Africa, and Central America. Although the zonal mean precipitation coincides with this result, the inter-model variability is large in low- to mid-latitudes. The normalized precipitation change is defined as WEM of the precipitation change divided by the standard deviation of the change among the fifteen models. When absolute value of the normalized precipitation change becomes more than 1, the inter-model variability of the precipitation change is less than the WEM of the precipitation change. In other words, common signal is discerned where the normalized precipitation is large. The precipitation likely increases at east Asia (+0.2mm/day), high latitudes (+0.1mm/day), and a part of central Africa (+0.5mm/day), and decreases in Mediterranean region (-0.2mm/day), a part of southern Africa (-0.2mm/day), and central America (-0.5mm/day).

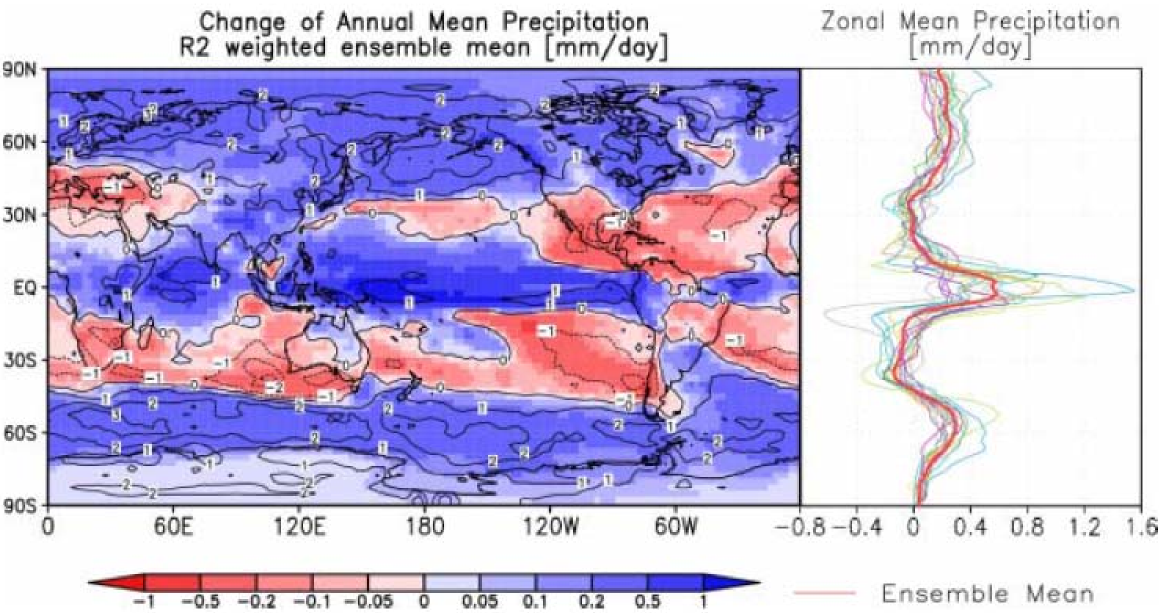


Figure 3.3: *Change of the annual mean precipitation (mm/day). The colour shading at left shows the change of WEM of the annual mean precipitation for the future (2100) against the present (1981-2000). The contours on the left show the normalized precipitation change. The change of the zonal mean precipitation for individual model (thin curves) and WEM (solid red curve) are shown on the right.*

The simulated precipitation is converted into runoff in the individual land surface model. Figure 3.4 illustrates the changes of annual mean and runoff in the future against the present. The patterns of the runoff changes are similar to the precipitation change. However, the highly reliable area of runoff, which is shown by the normalized runoff change, is smaller than the precipitation change. In other words, it is suggested that the projection of the runoff change is more difficult because the simulated runoff includes much uncertainty for the imperfect land surface scheme. The area of decreased runoff is distributed in Mediterranean to central Eurasia and central North America. In these regions, the runoff decreasing is sensitive to the precipitation reduction. On the other hand, in Asia monsoon, Amazon and Arctic tundra regions, the runoff increasing is sensitive to the precipitation increasing.

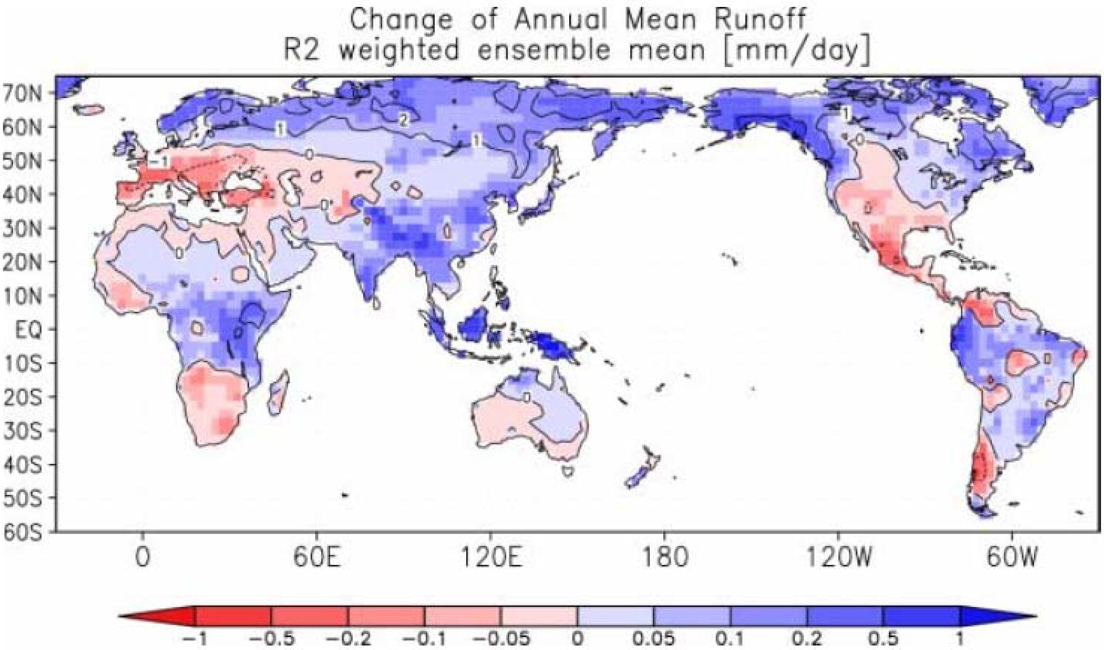


Figure 3.4: *Change of the annual mean runoff (mm/day). The colour shading shows the change of WEM of the runoff for the future (2100) against the present (1981-2000). The contour shows the normalized runoff change.*

Figure 3.5 shows the change in average annual runoff as simulated across the world under the SRES A2 emissions scenario and different climate models (Arnell, 2003). There are some generally consistent patterns of change – increases in high latitudes and the wet tropics, and decreases in mid-latitudes and some parts of the dry tropics – the magnitude of change varies between climate models, and in some regions – such as southern Asia – runoff could either increase or decrease. Under B2 emissions, patterns of change are similar but magnitudes of change are smaller. Studies which have simulated past variability as well as possible future changes (Douville *et al.*, 2002) show that future trends are not necessarily simple extrapolations of trends in the river flows over the 20th century.

The climate change signal is greater than the effect of natural decade-to-decade variability across much of the world by 2050, under A2 emissions. At a more local scale, studies have shown that climate change effects may be visible (and implicitly statistically detectable) as early as in the 2020s (Dettinger *et al.*, 2004), particularly where changes in temperature are producing changes in the timing of streamflows. Where hydrological regimes are more sensitive to changes in precipitation than to changes in temperature, it is possible that the effects of climate change will take longer to detect.

Figure 3.6 shows the smoothed time series of the global mean of the runoff change relative to the present years for WEM and the individual model. The smoothed curves are created by 10-year running mean. The runoff of most of models and WEM exhibits increasing trend, but inter-model variability of the runoff change is larger than the precipitation change. The global mean of the runoff change of WEM for the year 2090s increases by 8.7% (0.054mm/day) which is also larger than the precipitation change.

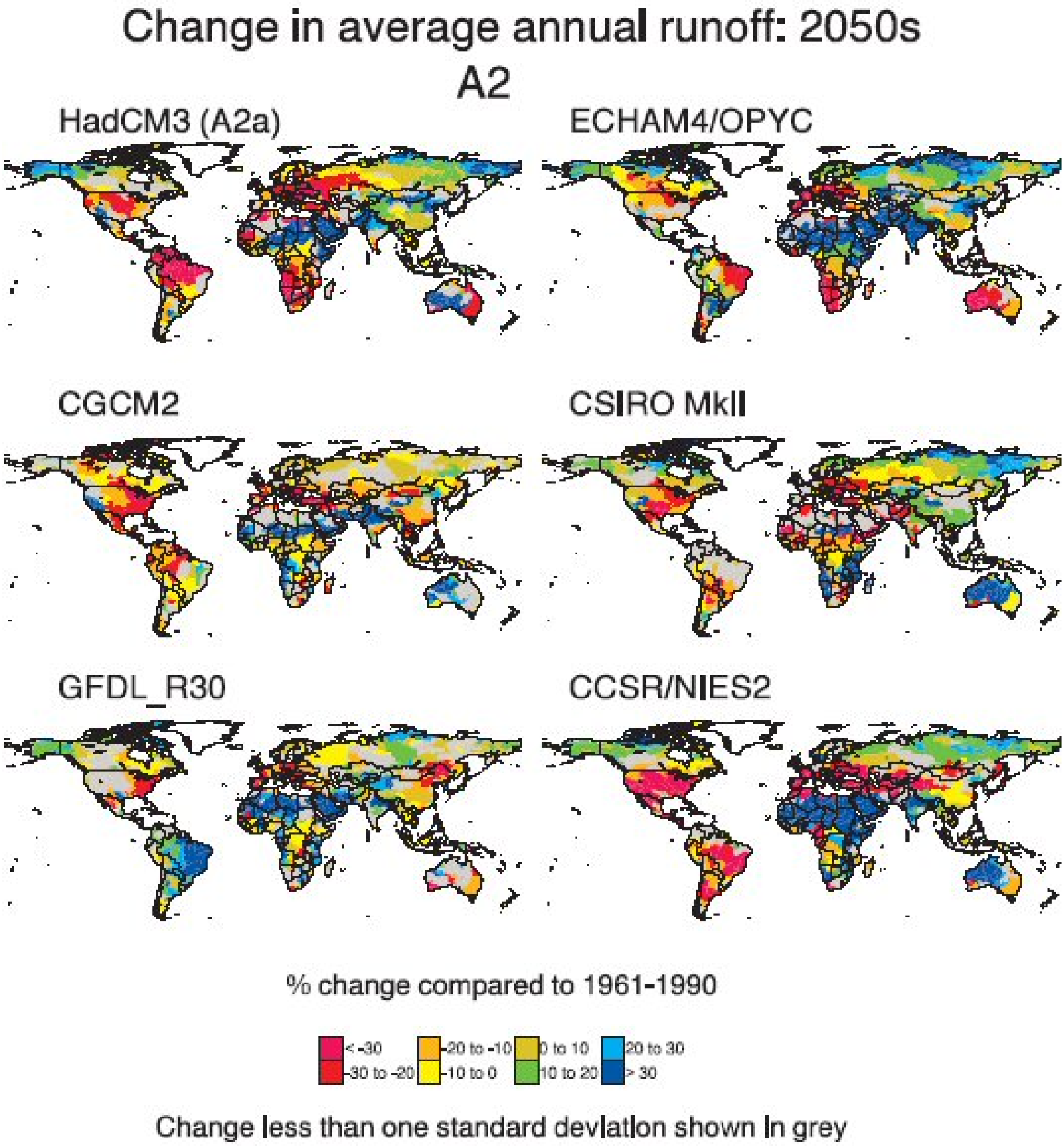


Figure 3.5: *showing the change in average annual runoff as simulated across the world under the SRES A2 emissions scenario and different climate models (Arnell, 2003).*

Figure 3.7 illustrates the change of simulated annual mean discharge compared to present converted from river runoff using river routine scheme GRiveT (Hosaka *et al*., 2005) which utilise the Total

Runoff Integrated Pathway (Oki and Sud, 1998). Although the pattern of the change of the discharges is similar to that of precipitation, it should be emphasized that the change of runoff at upstream region affects the discharge of the downstream. For example, the runoff at the mouth of the Euphrates river (50E, 30N) increases in the future although the discharge decreases more than 20 %, and at the Nile (30E, 30N) the runoff decreases although the discharge increases.

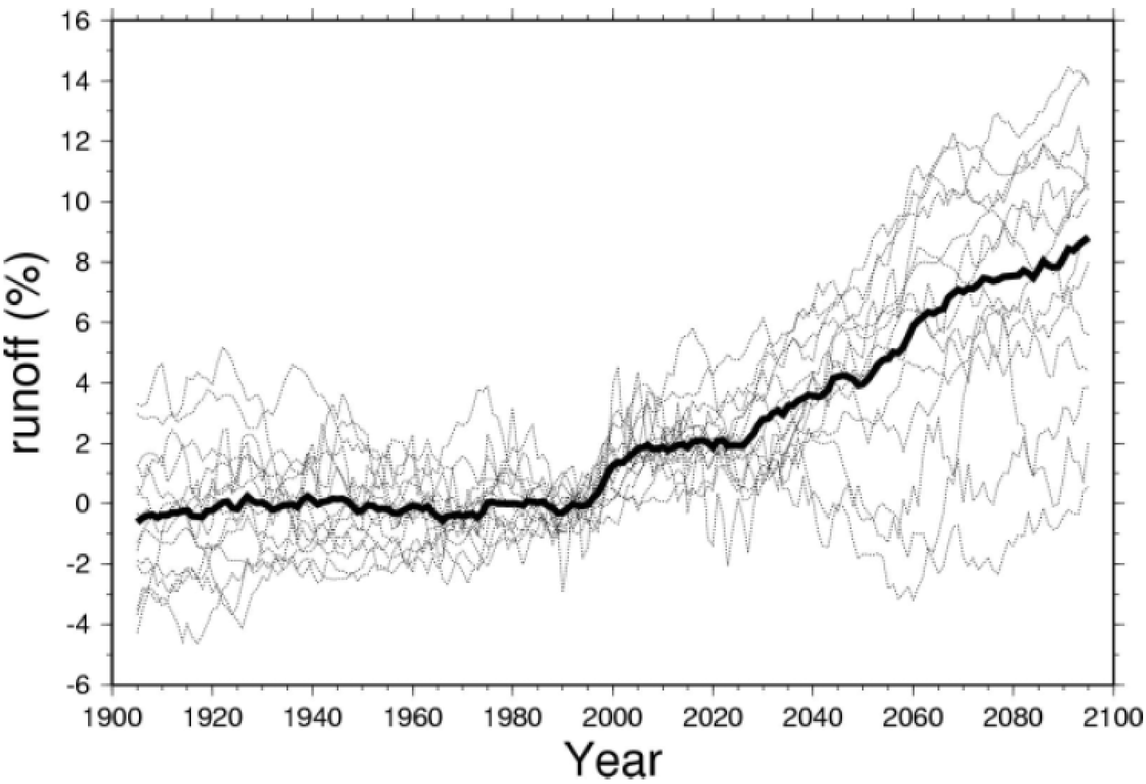


Figure 3.6: *Smoothed time series of the land mean runoff change relative to the present for individual model (dotted curves) and WEM (solid curve). The smoothed curves are the 10-year running mean.*

The annual mean of the discharge at the Amazon and Congo slightly increases (+5%) for the future. However, those trends may be statistically insignificant considering the range of the uncertainty due to the small normalized runoff change in Fig. 3.4. The decreasing trends of the annual mean discharge at the Euphrates (-41%), Syr Darya (-12%) and Rio Grande River (-26 %) are projected by WEM. In particular, the discharges at the Euphrates and Syr Darya clearly decrease during high-water season. On the other hand, the annual mean of the discharge at the Huang He and Nile increases (+10% and +14%, respectively) because of the increase of the runoff at the upstream. The discharges of the Danube and Rhine clearly decrease for the future (-23% and -12%, respectively) because the decrease of the precipitation is evidently shown from the Mediterranean area to the Caspian Sea in Figs 3.3 and 3.4. The future discharge at the Mississippi is similar to the present. At the Volga, the discharge increases during low water season, and decreases during high water season. Then the annual mean discharge results in increasing trend (+10%). The amounts of discharge of the Changjiang (Yangtze), Ganges and Mekong increase (+6%, +15% and +7%, respectively) for the future. However, those trends may be statistically insignificant considering the range of the uncertainty due to the small normalized runoff change in Fig. 3.4. The amounts of the discharge in the high latitudes (Amur, Lena, Mackenzie, Ob, Yenisei and Yukon) change evidently increase (+15%, +24%, +16%, +10%, +15% and +23%, respectively) due to the significant increase of the precipitation in Fig. 3.3. The average discharge for the four rivers (Lena, Mackenzie, Ob and Yenisei) into the Arctic Ocean increases by 16%, which is smaller than the estimation by Peterson *et al.* (2002) and Arnell (2005).

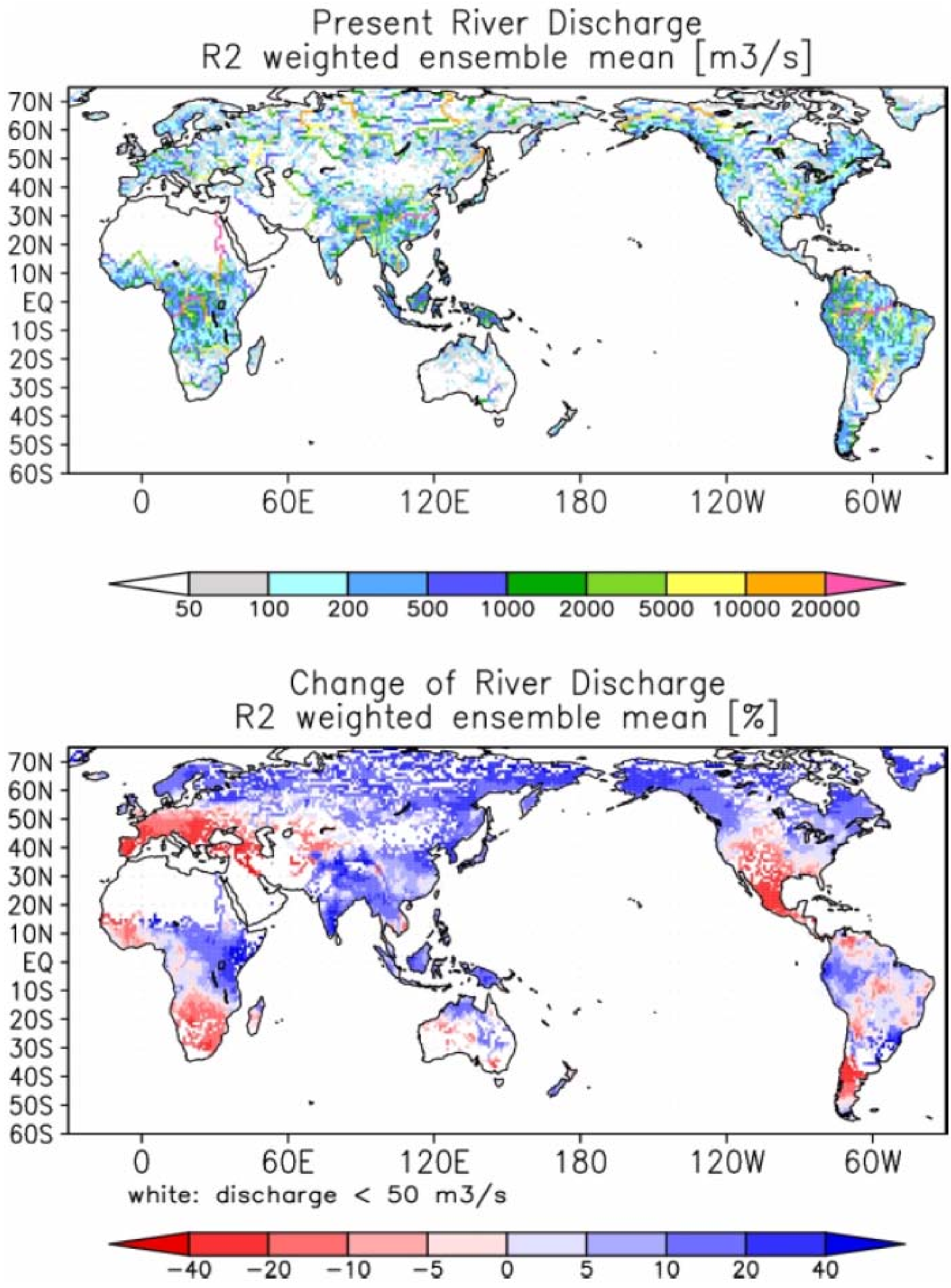


Figure 3.7: *(top) Simulated annual mean discharge for present (1980-2000) by the WEM (m3/s), (bottom) discharge change for 2100 relative to the present years (%).*

The precise conclusions of the catchment-scale studies listed in Table 3.1 depend on the climate scenarios, the hydrological model, and the methods used to apply the scenarios. However, it is possible to draw some generalised conclusions from the catchment studies.

Firstly, and most robustly, higher temperatures affect the timing of streamflows where much winter precipitation currently falls as snow. This has been found in the European Alps (Eckhardt & Ubrich, 2003; Andreasson *et al.*, 2004; Jasper *et al.*, 2004; Zierl & Bugmann, 2005), the Himalayas (Singh, 2003; Singh & Bengtsson, 2004), western North America (Loukas *et al.*, 2002; Stewart *et al.*, 2004; Payne *et al.*, 2004; Vanrheenen *et al.*, 2004; Dettinger *et al.*, 2004; Knowles & Cayan, 2004; Leung *et al.*, 2004; Christensen *et al.*, 2004; Hayhoe *et al.*, 2004; Maurer & Duffy, 2005; Kim, 2005), central North America (Stone *et al.*, 2001; Jha *et al.*, 2004) and eastern North America (Frei *et al.*, 2002; Chang, 2003). The effect is greatest at lower elevations (where snowfall is more marginal: Jasper *et al.*, 2004; Knowles & Cayan, 2004), and in many studies brings forward the peak flow season by at least a month. Winter flows are increased, and summer flows decreased.

For North Eurasia greater intensities and values of precipitation as well as an increases in river discharge are projected (Mokhov, 2002, 2003, 2004).

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

Although very few studies have explored the potential effects of changes in year to year climatic variability, several have demonstrated how year to year variability in runoff can increase even with no change in climatic variability (Yu *et al.*, 2002; Shabalova *et al.*, 2003; Arnell, 2003b; Jha *et al.*, 2004; Booij, 2005), due to the non-linear relationship between rainfall and hydrological response.

Climate is not the only influence on hydrological regimes that may change over the next few centuries, and in many catchments there may be changes in land use, land cover and other direct human interventions such as impoundments and abstractions. Feasible land-use changes have a (modelled) small effect on annual runoff relative to climate change in the Rhine basin (Pfister *et al.*, 2004), south east Michigan (Barlage *et al.*, 2002), Pennsylvania (Chang, 2003) and central Ethiopia (Legesse *et al.*, 2003). In other areas, however, such as south east Australia (Herron *et al.*, 2002) and southern India (Wilk & Hughes, 2002), land-use and climate-change effects may be more similar. In the Australian example, climate change has the potential to exacerbate considerably the reductions in runoff associated with afforestation.

Methodological advances since the Third Assessment Report have focused on exploring the effects of different ways of downscaling from the climate model scale to the catchment scale (e.g. Wood *et al.*, 2004), the use of regional climate models to create scenarios or drive hydrological models (e.g. Arnell *et al.*, 2003; Shabalova *et al.*, 2003; Andreasson *et al.*, 2003; Payne *et al.*, 2004), 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 ultimate source (a global-scale climate model) can lead to substantial differences in the estimated effect of climate change, but that hydrological model uncertainty is generally small compared to errors in the modelling procedure or differences in climate scenarios (Jha *et al.* 2004; Arnell, 2005).

3.4.2 Soil water and evapotranspiration

Soil moisture is an indicator of agricultural drought which is distinguished from meteorological drought (less rainfall) and hydrological drought (less river discharge), and it is concerned a lot particularly in terms of the crop yield and agricultural production. The change in soil moisture due to the climate change is determined by the balance between the changes of precipitation and evapotranspiration. In semi arid region where incoming solar energy is plenty compared to the available evaporative water stored as soil moisture, evapotranspiration is controlled by the availability of soil water originated from precipitation, and change in precipitation influences evapotranspiration change. Particularly, decrease in precipitation results decrease of soil moisture to suppress the evaporation from land surface.

From a GCM simulation assuming the condition of quadrupling of atmospheric carbon dioxide, it is reported that annual mean soil moisture decreases in many semi-arid regions of the world, such as south-western part of North America, Mediterranean coast, the north-eastern region of China, the grasslands of Africa and the southern and western coast of Australia, and over very extensive regions of the Eurasian and North American continents in middle to high latitudes, soil moisture decreases in summer but increases in winter, in contrast to the situation in semi-arid regions; in summer, the percentage reduction exceeds 30% over certain regions of Siberia and Canada, and soil moisture increases substantially in these regions in winter (Manabe *et al.*, 2004).

The vast majority of hydrological impacts assessments assume that increasing CO_2 concentrations have no direct effect on rates of evaporation. Where stated, it is assumed that the effects of reduced stomatal conductance are offset at the catchment scale by increased plant growth, resulting in small net effect on regional transpiration. The relative significance of these two competing drivers can now be assessed using process-based vegetation models (e.g. Gordon & Famiglietti, 2004; Gerten *et al.*, 2004), although the form of model affects implied sensitivity to change. Changing CO_2 concentrations alone could lead to statistically significant reductions in runoff in high latitudes and the wet tropics (Gerten *et al.*, 2004), but increases in some water-stressed regions where increased water-use efficiency could mean that forests would take over from grassland. Simulations using a different model across the United States (Rosenberg *et al.*, 2003) showed that combining the effects of CO_2 enrichment with changes in climate led to larger increases in runoff across most of the United States, and in some regions changed a reduction in runoff to an increase, but the effects of CO_2 enrichment, were small relative to the effects of climate change. The direct implications of increasing CO_2 concentrations for regional evaporation, and hence runoff, however, remain uncertain.

Based on the simulated precipitation (cf. Fig. 3.3), evaporation is calculated in the individual land surface model. Figure 3.8 illustrates changes of annual mean evaporation in the future against the present. The patterns of the evaporation changes are similar to the precipitation change (Fig. 3.3).

Studies of terrestrial or global evaporation using future predictions by AGCMs (e.g., Douville *et al.*, 2002; Bosilovich *et al.*, 2005) are already available, though we need few more years to draw reliable conclusions out of them.

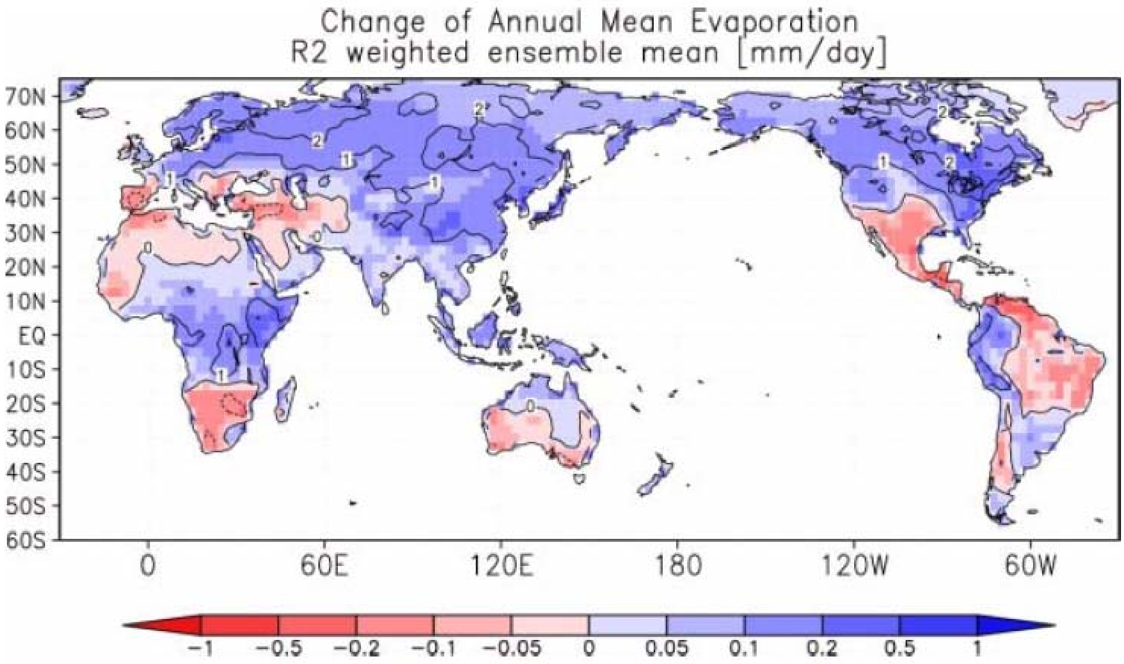


Figure 3.8: *Change of the annual mean evaporation (mm/day). The colour shading shows the change of WEM of the evaporation for the future (2100) against the present (1980-2000). The contour shows the normalized evaporation change.*

3.4.3 Snow and ice *[To be provided by a Contributing Author who has already been contacted]*

The widespread glacier retreat is all the more notable because tropical mountain glaciers are old, having survived thousands of years of natural climate fluctuations. The Northern Ice Field on Kilimanjaro may be gone in as little as twenty years, after having survived the past 11,000 years (Pierrehumbert, 2005).

If the recent climatic conditions continue, a complete extinction of a small Chacaltaya Glacier in Bolivia (16^{o}S) can be expected before 2015 (Francou & Coudrain, 2005). This glacier is representative to Bolivian eastern cordilleras, where 80% of glaciers are small (below 0.5 km^2). A probable extinction of these glaciers in the near future could seriously affect the hydrological regime and the water resources (Ramirez *et al.*, 2001).

[At present – placeholder. To be cross-checked with WG1]

3.4.4 Groundwater

There has been very little research on the impacts of climate change on groundwater. Future decrease of groundwater recharge (being severe in dry years) was projected for climate models predicting less summer and more winter precipitation, using a coupled groundwater and soil model for a groundwater basin in Belgium (Brouyere *et al.*, 2004). For a highly permeable, unconfined aquifer located in the humid north-eastern U.S., climate change result, in 2030 and 2100, in either slightly higher, no different, or significantly less annual recharge and groundwater elevations, producing a variety of impacts on wetlands, water supply potential, and low flows. Impacts are most severe under some drought scenarios (Kirshen, 2002). Under certain circumstances (good hydraulic connection of river and aquifer, low groundwater recharge rates), changes in river flows and thus stages influence groundwater levels much stronger than changes in groundwater recharge (Allen *et al.*, 2003). With respect to groundwater quality, climate change is likely to have a strong impact on coastal salt water intrusion as well as on salinization of groundwater. For two small and flat coral islands off the coast of India, the thickness of the freshwater lens was computed to decrease from 25 m to 10 m and from 36 to 28 m, respectively, for a sea level rise of only 0.1 m (Bobba *et al.* 2000). In addition to the sea level rise, any change in groundwater recharge affects the location of the freshwater/saltwater interface, and saltwater intrusion is expected to increase if less groundwater recharge occurs. This can also happen inland where saline water is located next or below freshwater (Chen *et al.*, 2004). For many semi-arid areas, a decrease in precipitation is projected and enhanced evapotranspiration in the warmer world might cause a salinization of groundwater.

According to the results of a global hydrological model, groundwater recharge (when averaged globally), will increase less than total runoff (Döll, 2005). While total runoff (groundwater recharge plus fast surface and subsurface runoff) was computed to increase by 9% between the climate normal 1961-1990 and the 2050s (for the ECHAM4 interpretation of the SRES A2 emissions scenario), groundwater recharge only increases by 2%. This is mainly due to the limited infiltration capacity of the soil which, in many areas of increasing total runoff (in particular in the monsoonal regions of Asia and in the humid parts of South America) decreases the groundwater recharge to total runoff ratio. However, there are also regions where this ratio increases due to seasonal shifts of precipitation and temperature. For all of the investigated four climate scenarios, computed groundwater decreases dramatically by more than 70% in north-eastern Brazil, southwest Africa and along the south rim of the Mediterranean Sea (Fig. 3.9). In these areas of decreasing total runoff, the percent decrease of groundwater recharges is higher than the percent decrease of total runoff, which is due to the model assumption that in semi-arid areas, groundwater recharge only occurs if daily precipitation exceeds 10 mm. Regions with groundwater recharge increases of more than 30% until the 2050s include the Sahel, the Near East, Northern China, Siberia and the Western USA. There, rising groundwater might cause problems e.g. in urban areas or with respect to soil salinization.

Provision of sufficient water of good quality under growing water demands and increasing climate variability will be one of the main concerns for water managers in the coming decades (Tuinhof *et al.*, 2004). It is necessary to develop groundwater resources management programs by considering regional variations in water quality. Higher sea levels associated with thermal expansion of the oceans and increased melting of glaciers will push salt water further inland in rivers, deltas, and coastal aquifers [very high confidence], thus adversely affecting the quality and quantity of freshwater supplies in many coastal areas.

Recent observations in the Arabian Peninsula along the Red Sea coast have shown that climate change may increase both the frequency and the magnitude of floods, which are the major sources of groundwater recharge and aquifer storage (Al-Sefry *et al.*, 2004).

Şen *et al.* (2003) suggested artificial groundwater resources mixture in order to reduce the saltwater intrusion into the coastal aquifers. Increased precipitation pollution (acid rain) is likely to affect groundwater quality in different manners. A water balance model results indicate that overall global warming is likely to lead to reduced water holding capacities, that is increased water runoff during wet periods, and in consequence - higher overland flow rates and reduced recharge rates to groundwater (Feddeman and Freire, 2001).

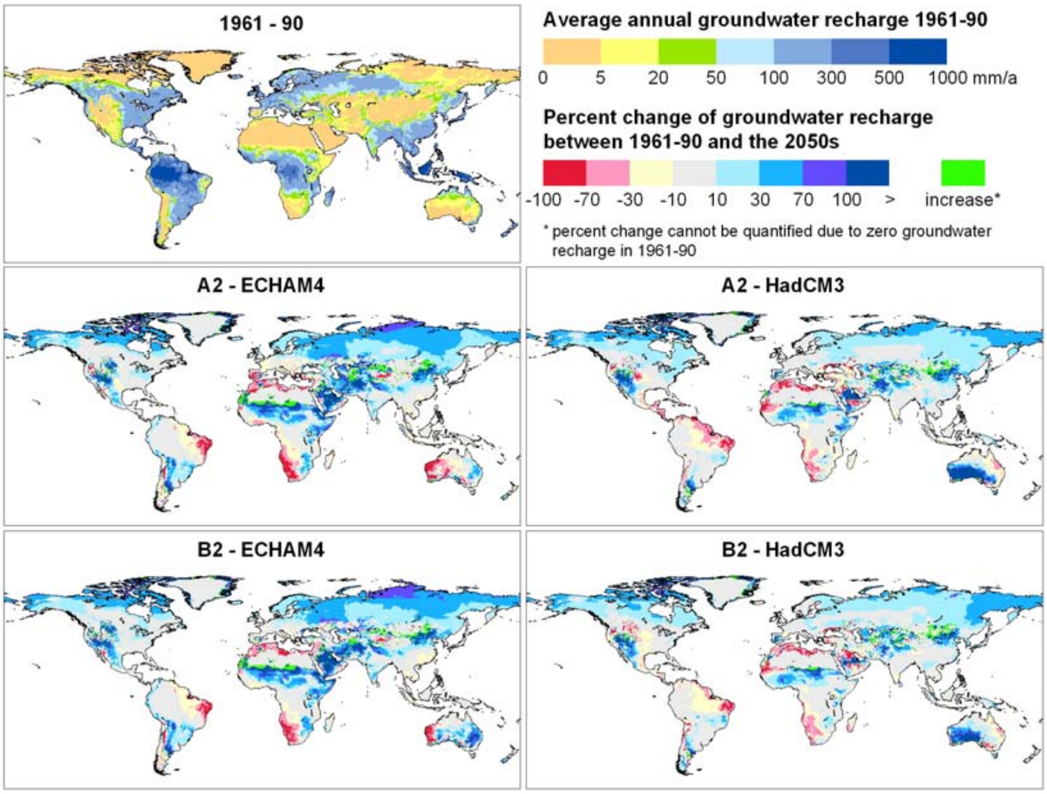


Figure 3.9: *Impact of climate change on long-term average annual diffuse groundwater recharge. Percent changes of 30-year averages groundwater recharge between 1961-1990 and the 2050s (2041-2070), as computed by the global hydrological model WGHM, applying four different climate change scenarios (climate scenarios computed by the climate models ECHAM4 and HadCM3, each interpreting the two IPCC greenhouse gas emissions scenarios A2 and B2) Döll, 2005.*

Aquifers in arid and semi-arid regions are replenished by floods and therefore flood inundation areas are among the most significant groundwater recharge locations. Accordingly, their extents must be delimited by taking into account the future climate change effects (Khiyami *et al.*, 2005). It is very likely that the unconfined or shallow aquifers will be affected by climate change more significantly [high confidence]. On the other hand, deep and especially confined aquifers are not in direct contact with the present-day hydrological cycle and they are very unlikely to be affected by climate. The potential impacts of climate change will be strongest in fractured and karstic aquifers which are most responsive to changes in recharge as typically they have low specific yields (i.e. they have drainable porosities) in comparison with porous flow systems.

In countries, which are poor in water resources, the desalination plants will be used to conserve groundwater resources as strategic planning assets for future generations (sustainable development concerns), or emergency situations (Al-Sefry, *et al.*, 2004), since continual withdrawal in excess of recharge and possible climate change effects would ultimately remove all of the recoverable water [medium confidence].

3.4.5 Floods, droughts and their impacts

Based on the results of the climate models, it is projected that over many areas the hydrological cycle will intensify, i.e. floods and droughts will become more extreme. Yet there are a number of non-climatic factors exacerbating flood and drought losses, such as decrease in storage capacity in catchments, excessive water withdrawals, human encroaching into flood plains around urban areas, etc.

It is very likely that heavy precipitation events will increase over many areas of the globe, and it is likely that summer dryness will rise over most mid-latitude continental interiors (***newer references***). Recent works on changes in precipitation extremes in Europe (Giorgi *et al.*, 2004; Räisänen *et al.*, 2004) agree that the intensity of daily precipitation events will predominantly increase, even in regions where the mean annual precipitation will decrease (Christensen & Christensen, 2003, , Kundzewicz *et al.*, 2004). The number of wet days will decrease according to Giorgi *et al.* (2004), which leads to longer dry periods except in the winter of West and Central Europe. Increase of the number of days with intense precipitation has been projected in Europe (Kundzewicz *et al.*, 2004).

Palmer & Räisänen (2002) analyzed the modelled differences between the control run with 20th century levels of carbon dioxide and an ensemble with transient increase in CO_2 and calculated around the time of CO_2 doubling (61-80 years from present). They found a considerable increase of the risk of a very wet winter in Europe and a very wet monsoon season in Asian monsoon region. The modelling results indicate that the probability of total boreal winter precipitation exceeding two standard deviations above normal will considerably increase over large areas of Europe. For example, an over five-fold increase is projected over parts of British isles and much of the Baltic Sea basin, and even over seven-fold increase for parts of Russia.

Milly *et al.* (2002) demonstrated that for 15 out of 16 large basins (over 200 000 km^2) they analyzed, the control 100-year flood is exceeded more frequently as a result of CO_2 quadrupling. In some areas, what is given as a 100-year flood in the control run, is projected to become much more frequent, even occurring as often as every 2 to 5 years and particularly strong increases are projected in Northern Asia. Milly *et al.* (2002) found that the likelihood that these changes are due to natural climate variability is small.

In many parts of Europe, significant changes in flood or drought risk are expected under IPCC IS92a scenario (similar to SRES A1) for the 2020s and the 2070s (Lehner, 2005). The regions most prone to a rise in flood frequencies are northern to 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 the ECHAM4 and the HadCM3 model (Fig. 3.10). In the critical regions, events with an intensity of today’s 100-year floods and droughts may recur every 10-50 years by the 2070s. The study results are based on changes in monthly precipitation (and temperature) values only. The expected future increase of precipitation variability at the daily scale is not taken into account, so that increases in flood frequencies are very likely to be underestimated.

The 21st century, featuring further dynamic demographic growth, is heralded as the age of water scarcity. Droughts should not be viewed as exclusively physical or natural phenomena (Kundzewicz *et al.*, 2002). Their socio-economic impacts may actually arise from the interaction between the natural conditions and the human factors - decrease in storage capacity in catchments, adverse land-cover changes, and changes in water demand, use, and consumption. Water withdrawal from rivers is a process of considerable importance in the low flow context. Hence, human water consumption effectively exacerbates the impact of drought.

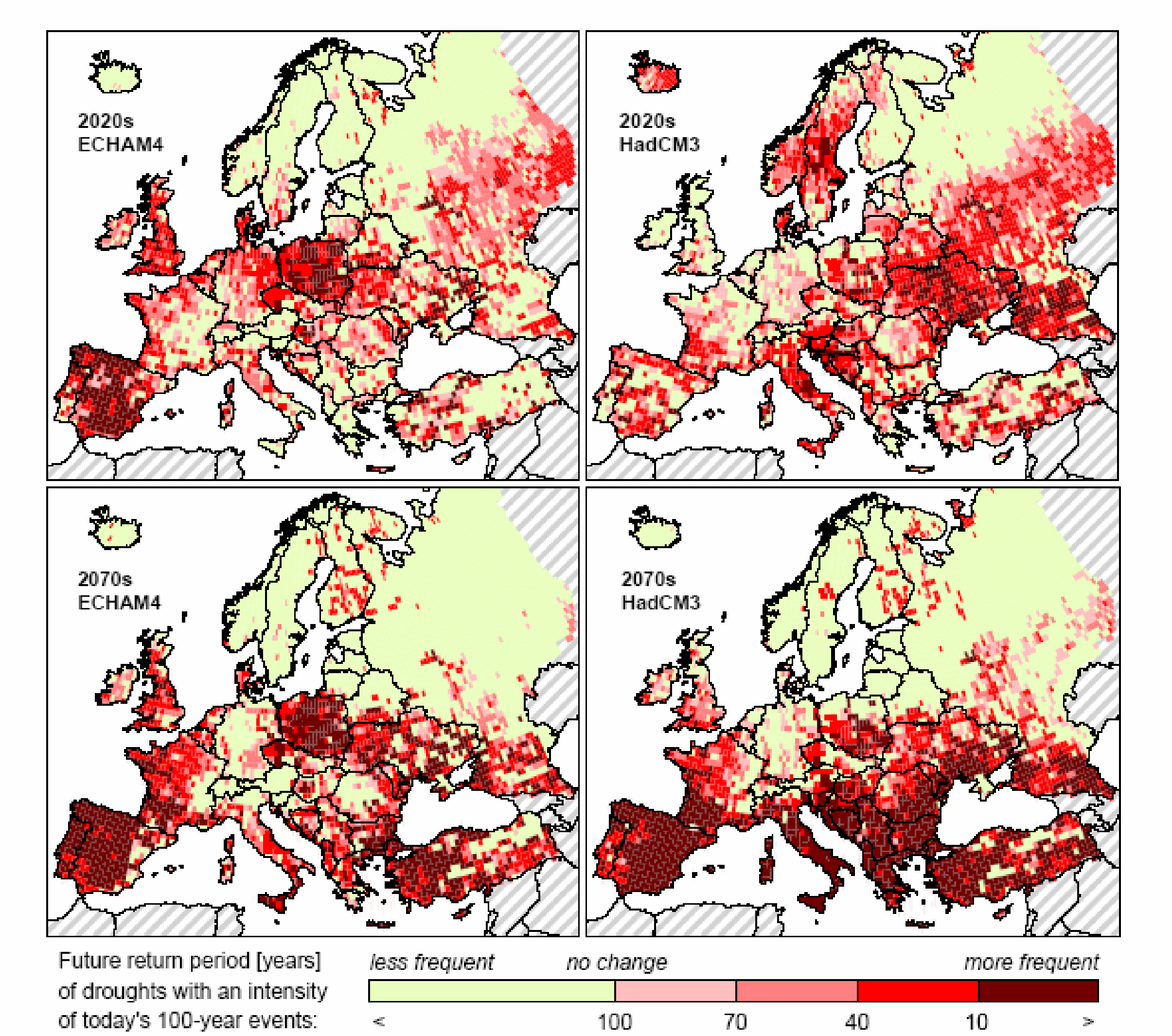


Figure 3.10: *Change in recurrence of 100-year droughts, based on comparisons between today's climate and water use (1961-90) and simulations for the 2020s and 2070s (ECHAM4 and HadCM3 climate models, emissions scenario IS92a and a business-as-usual water use scenario). Values calculated with WaterGAP 2.1. Lehner, 2005.*

Decrease in summer precipitation in Southern Europe, accompanied by growing temperatures, which enhance evapotranspiration, would inevitably lead to more frequent and more intense droughts. This is of considerable concern in the light of the 2003 summer drought in Southern Europe, which is being considered as a possible analogue of future conditions (refs.: Schär+, Beniston+). Growing summer temperature, especially if superimposed on decreasing precipitation, will lead to the increase in severity of droughts. In warmer winter conditions, with more rain and less snow, snowmelt is earlier and less abundant, and this may lead to rising risk of droughts in the vegetation season.

Projected increase in summer drying over mid-latitude continental interiors and in associated drought risk would lead to a number of adverse impacts, such as: decreased crop yields; increased damage to building foundations caused by ground shrinkage; decreased water resource quantity and quality; and increased risk of forest fire.

One can conclude that in addition to non-climatic factors, such as changes in terrestrial systems and in socio-economic systems, climate change is likely to affect flood and drought hazard with growing strength, and many impacts will be adverse.

3.4.6 Water availability and use

With respect to the impact of climate change on water availability and use, semi-arid and arid drainage basins are the most vulnerable regions of the globe. This is a common result of a number of global-scale (Arnell, 2004, scenario; Alcamo, 2002, critical; Millennium Ecosystem Assessment, 2005), national-scale (Thomson, 2005) and basin-scale assessments (Barnett, 2004, impact). In many of these basins, water stress is already high today: the per-capita water resources are low and/or the ratio of water withdrawals and water resources is high. Thus, any considerable reduction in runoff will make it impossible to fulfil even current water demands. In the case of the Sacramento-Joaquin River and the Colorado River basins in the Western USA, the streamflow changes as computed based on the results of a selected climate model are so strong that around 2020, 2050 and 2080, not all the present-day water demands (including environmental targets) could be fulfilled any more even with an adapted reservoir management (Barnett, 2004, impact). This is due to a seasonal shift of streamflow mainly governed by temperature change impacts on snow, while precipitation reductions are rather small. The actual water stress is very likely to be much larger as (1) the employed climate model has a fairly low climate sensitivity, such that the projected temperature increase (which strongly impact the assessment results) might be underestimated, (2) the expected increase in precipitation variability is not taken into account (as in virtually all climate change impact studies) and (3) the expected considerable growth of human water demands is not taken into account.

Whether climate change will lead to decreased (annual and seasonal) runoff in a given river basin is uncertain due to the high uncertainty of precipitation changes as computed by global and regional climate models (e. g. Thomson, 2005; Rosenzweig, 2004; Arnell, 2004; Döll, 2003; Andreasson, 2004; Wechsung, 2004). However, computed changes, in percent of current runoff, are particularly high in semi-arid river basins; for example up to ± 50% in the Midwest and Southwest USA (Thomson, 2005, water resources).

Most semi-arid river basins in developing countries are even more vulnerable to climate change than the basins of the Western USA, as population and thus water demand in most of these basins is expected to grow rapidly in the future, and coping capacity is low (Millennium Ecosystem Assessment, 2005). The latter refers in particular to rural population without access to public water supply, which 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 currently not overused (expressed as low water use to availability ratio or high per capita water availability), climate change 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 availability and use. River discharge reduction in the Rhine basin during the dry summer period (due to changes in snow and glacier melting) may be 5-12% in 2050, which may negatively influence navigation and water supply in particular for thermal power plants (Middelkoop, 2001). The reliability of water supply for irrigation does not decrease significantly in most cases due to the impact of climate change in major maize and soybean growing river basins in Hungary and Romania, Argentina and Brazil, China, and the United States for the 2020s and the 2050s (Rosenzweig, 2004) considering five climate scenarios and two scenarios of changed domestic and industrial water use. This, however, is due to the climate scenarios which mostly predict increases in runoff.

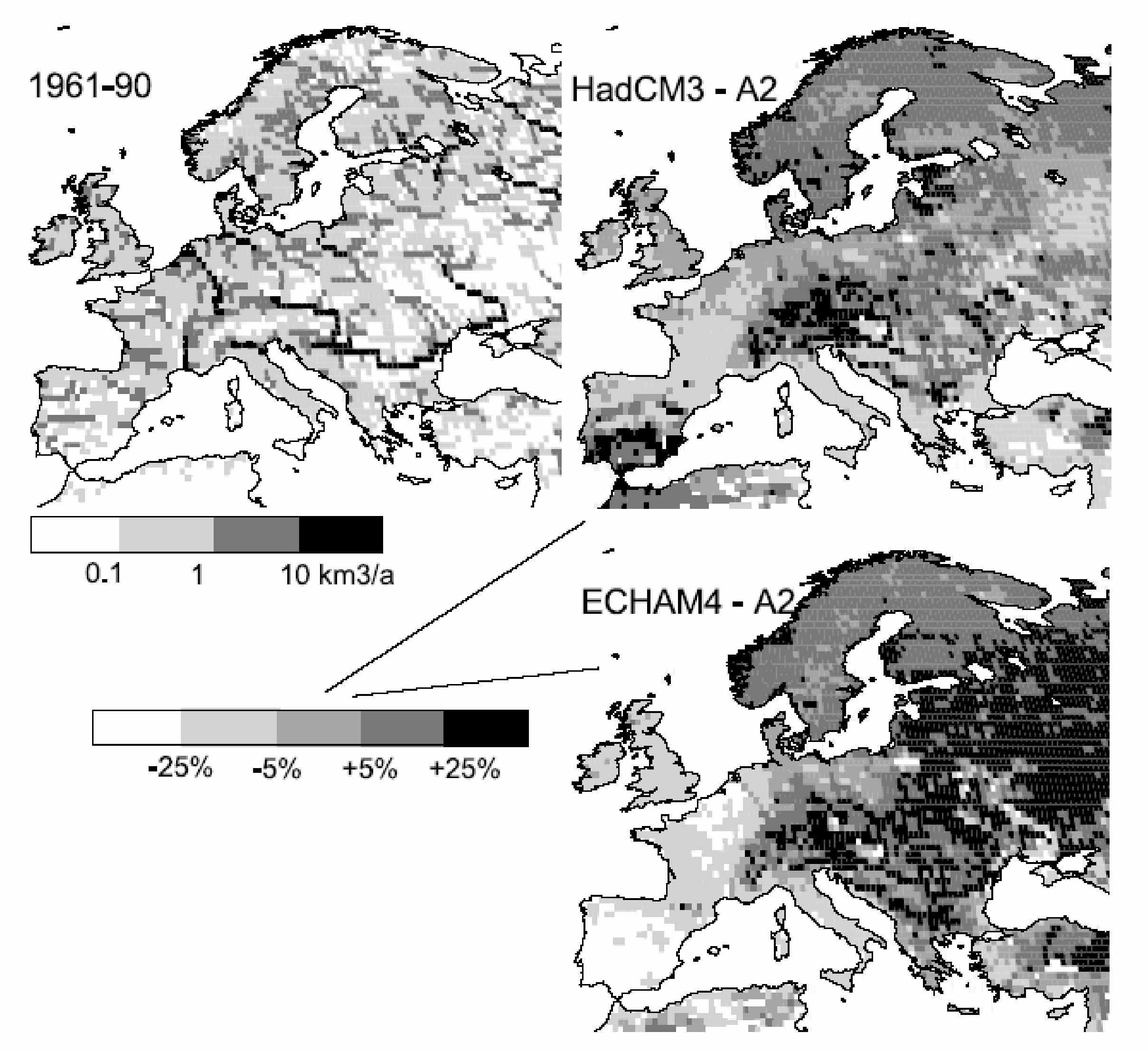


Figure 3.11: *90% reliable monthly river discharge Q_{90} [km^3/a] as indicator of water availability in each 0.5° grid cell during the climate normal 1961-90 (left). Change of Q_{90} until the 2020s for emissions scenario A2 correspond to simulations by HadCM3 und ECHAM4 models. Computations with WaterGAP 2.1 Döll, 2005.*

In most global-scale assessments of climate change impacts on water availability, water availability is assumed to be equal to the long-term average renewable water resources of a grid cell or a river basin (Arnell, 2004; Alcamo, 2005; Alcamo, 2003; Vörösmarty, 2000). However, long-term averages are the upper limit of water that can be made available, and therefore, to better represent the water volumes available for safe water supply, it is useful to consider the impact of climate change on indicators that take into account temporal variability of water supply. This includes the runoff that is exceeded in nine out of ten years (Arnell, 2004) and the river discharge that is exceeded in nine out of ten months (Alcamo, 2005; Döll, 2005). Figure 3.11 shows, for Europe, the latter statistical monthly low flows may increase in Northern and Eastern Europe, but results for the rest of Europe depend strongly on the applied climate model dependent climate scenarios. However, as described in section 3.3.1, these hydrological studies only considered the impact of climate change on long-term average monthly climate variables, which leads to an underestimation of future climate variability. Thus, for example, statistical low flows as an indicator of water availability are probably overestimated in this type of climate impact study.

In global-scale studies of water availability, various indicators are used to express water stress, most often long-term average water resources per capita (Arnell, 2004) or the water withdrawals to water resources ratio (Alcamo, 2005; Alcamo, 2003; Vörösmarty, 2000). According to all these studies, climate change is but one factor that influences future water stress, while demographic, socio-economic and technological changes may, in most time horizons and regions, play a more important role. In the 2050s, differences in the population development in the four IPCC SRES scenarios are more important for the number of people living in water-stressed river basins (defined as basins with per-capita water resources of less than 1000 m^3/year) than the differences in the emissions scenarios (Arnell, 2004). In the A2 scenario, 262-983 million people move into the water-stressed category, and 1092-2761 million people in water-stressed river basins become more stressed, while in the B2 scenario, the ranges are 56-476 million and 670-1538 million, respectively. The ranges are caused by the differing results of the various climate models applied. Without climate change, the number of people living in severely stressed river basins increases significantly (Table 3.3). If the global number of people living in water-stressed river basins was taken as the indicator of water resources stress, then climate change would appear to reduce water stress. This is misleading, as (1) increases in runoff mainly occur during high flow seasons, and may not alleviate dry season problems if the extra water is not stored, and (2) the basins that apparently benefit from climate change are in limited but populous parts of the world, mainly in east and southern Asia (Arnell, 2004).

Table 3.3: *People living in water stressed river basins with renewable water resources of less than 1000 m3/yr per capita (Alcamo, 2005; Arnell, 2004), in million people. The differences between the estimates of Alcamo et al. and Arnell are possibly due to different assumptions on future population distributions or different geographic units of analysis (11050 river basins in the case of Alcamo et al., and 1300 river basins in the case of Arnell).*

	Without climate change, (percent of global population) according to (Arnell, 2004)	With climate change according the emissions scenarios (number of climate model runs)*, according to (Arnell, 2004)	With climate change according the emissions scenarios (number of climate model runs)*, according to (Alcamo, 2005)
1995		1368 (24%)	1601
A1 2050s	3400 (39%)	2512 (1)	
A2 2050s	5590 (48%)	4351-5747 (8)	6432-6920 (2)
B1 2050s	3400 (39%)	2757 (1)	
B2 2050s	3988 (42%)	2766-3958 (7)	4909-5166 (2)

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

If water stress is not only assessed as a function of population and climate change, but also of changing water use, the importance of non-climatic drivers (here income, water use efficiency, industrial production) even increases (Alcamo, 2005). Income growth has a much larger impact than population growth on increasing water use and water stress (as expressed as the water withdrawal-to-water resources ratio). The principal cause of decreasing water stress up to the 2050s (which is modelled to occur over 20-29% of the global river basin area, considering two global climate models and the IPCC scenarios A2 and B2) is the greater availability of water due to increased precipitation related to climate change. Increased precipitation is the most important factor on 53-83% of the area with decreasing water stress. The principal cause of increasing water stress (occurring over 62-76% of the global river basin area) is growing water withdrawals, and the most important factor for this increase is the growth of domestic water use stimulated by income growth. Increased water withdrawals are the most important factor leading to increasing water stress on 87-90% of the area. (Alcamo, 2005). Please note that irrigation area was assumed to remain constant in this study.

Withdrawal water use

Of all withdrawal water use sectors, the irrigation sector will be most affected by climate change. Climate change directly influences net irrigation requirements, while water withdrawals depend on the efficiency of irrigation water use, too. Higher temperatures alone lead to higher evaporative demand, which should be fulfilled by additional irrigation to allow for optimal plant growth. The predicted increased variability of precipitation, which includes longer drought periods, would lead to an increase of irrigation requirements, even if the total precipitation during the growing season remained the same (Eheart, 1999). Due to increased atmospheric CO_2 concentrations, water use efficiency of plants will increase, so that less water will be transpired to achieve the same amount of plant growth. Thus, the production of a certain crop mass will require less irrigation water, but with respect to the irrigation requirements of a certain irrigated area, the net effect of increased water use efficiency and a changed crop yield per area is generally unknown. Importantly, irrigated agriculture is highly adaptive to changed production conditions.

There are no global-scale studies which attempt to quantify the influence of all these climate-change related factors on irrigation water use; only the impact of climate change on optimal growing periods and net irrigation requirements has been modelled, assuming no change in irrigated area (spatial resolution 0.5° by 0.5°) (Döll, 2002, 2003). Applying the IPCC A2 and B2 emissions scenarios as interpreted by two climate models, it was found that the optimal growing periods will significantly shift in many irrigated areas. Net irrigation requirements of China and India, the countries with the largest irrigated areas, change by +2% to +15% and by -6% to +5% for the year 2020, depending on emissions scenario and climate model. Global net irrigation requirements increase by 1-3% until the 2020s and by 2-7% until the 2070s. As precipitation changes as computed by climate models do not correlate much with greenhouse gas emissions, it is not surprising that the highest increases of global net irrigation requirements result from a climate scenario that is based on the B2 emissions scenario (with lower emissions than the A2 scenario).

Demographic and socio-economic changes are likely to have a stronger effect on irrigation water use than climate change, even though local and regional impacts of climate change may be large. Not taking into account climate change, an increase in irrigation water withdrawals of 14% (300 km^3/yr) is foreseen until 2030 for the developing countries (Bruinsma, 2003), corresponding to areal extension of irrigated areas and the improvement of irrigation water use efficiency. The assumed increases in domestic and industrial water use are mostly larger that the increases in irrigation water use. In the four Millennium Assessment scenarios, global water withdrawals increase from 3600 km^3/yr around the year 2000 to 4100-6600 km^3/yr in 2050, with the lowest value in TechnoGarden and the highest in Order for Strength (Millennium Ecosystem Assessment, 2005); no information on the increase of irrigation water use or the climate change impact is provided.

On the national scale, an integrated assessments of climate change impacts on agriculture in the USA in 2030 and 2090 (Reilly, 2003) did not only consider the impact of changed monthly precipitation and temperature but also of CO2 concentrations. In addition, it took into account climate change impacts on crop production and river runoff to model changes in irrigation water withdrawals, combining everything by an agro-economic model. The IS92A emissions scenario for the USA as a whole and until 2030 results in temperature increase of 1.4°C and 2.1°C, respectively, for HadCM2 and CGCM1 models. Precipitation is predicted to increase by 6% by HadCM2 and to decrease be 4% by CGCM1. Regional variations of the changes in irrigation water withdrawals were large. On average, irrigation water withdrawals decrease by 5% in case of CGCM1 (32% until 2090) and by 12% in case of HadCM2 (38% until 2090), which is mainly due to a decrease in irrigated area. Irrigation is abandoned as the yield gap between irrigated and rainfed agriculture generally narrows as (1) yields decline due to high temperatures and (2) additional precipitation benefits rainfed agriculture more than irrigated agriculture. Another study on the adaptation by irrigation in the USA also found that under all climate change scenarios irrigated area in the USA decreases in the future(Thomson, 2005). In certain regions and scenarios, precipitation declines so much that water supplies are limited and very little cropland can be irrigated; in other scenarios precipitation is so plentiful that crop yields do not increase with irrigation so that it is not applied.

An analysis of the sensitivity of irrigation water withdrawals under profit-maximizing and yield-maximizing irrigation practices to mean and variability of precipitation, CO_2-concentration and temperature showed that withdrawals under profit-maximizing irrigation practice are most sensitive to the investigated factors (Eheart, 1999). Withdrawals are more sensitive to a 25% decrease in precipitation than to a temperature increase of 4°C, a doubling of CO2 or a doubling of the standard deviation of precipitation. With the 25% decrease in precipitation and the resulting increase in irrigation withdrawals, the frequency of historical 7-day 10-year low flows will strongly increase despite of streamflow accretion from groundwater-supplied irrigators.

Human in-situ water use

The capacity for hydropower generation is expected to increase in the future in many countries, in particular in developing countries with strongly increasing energy demands and high but not yet exploited hydropower potential. Thus, climate-change induced changes in river discharge are likely to have an important impact on the energy sector. A study on the impact of climate change on hydropower potential in Europe (Lehner, 2005) underlines that the potential of existing hydropower plants to produce electricity is strongly correlated to the changes in river discharge as predicted by a macro-scale hydrological model that is driven by the climate change scenarios of two global climate models. In the 2070s, Scandinavia and Northern Russia show an increase of their developed hydropower potential of 15-30% while Portugal, Spain, Ukraine, Bulgaria and Turkey will suffer from a decrease of 20-50% and more. For the whole of Europe, the developed hydropower potential shows a decrease of 7-12% until the 2070s.

Water requirements of aquatic ecosystems

If river discharges decrease due to climate change, negative impacts on both freshwater ecosystems and the coastal marine ecosystems can be expected. In the case of decreased discharge in the Western USA, the Sacramento and Colorado River deltas could experience, until 2050, a dramatic increase in salinity and subsequent ecosystem disruption, and in the Columbia River system will be faced with the choice of either spring and summer releases for salmon runs or summer and fall hydroelectric power production (Barnett, 2004). Worse, some salmon species could cease to exist due to climate change in the Pacific Northwest regardless of any water policies. In snowmelt-driven river, with decreased summer low flows, their will be increased competition for the decreased summer low flow water by agricultural users and those wishing to sustain endangered fish populations (Barnett, 2004).

For ephemeral wetlands and their shrimp populations in the Central Valley eco-region of California, USA, there exist strong interactions between habitat loss by land-use change and climate change (Pyke, 2005). These shrimp are restricted to wetlands that remain inundated long enough for reproduction but then dry quickly; a decrease of precipitation by 10% in the year 2100 would have a negative effect on the shrimps, and an increase of 30% a positive effect. However, biological reserves for three of the five species are biased towards drier areas, and if unprotected habitat were lost, the remaining habitat would show shorter and less frequent inundations even with higher precipitation. The frequency of bird-breeding event in the Macquarie Marshes in the Murray-Darling basin in Australia will decrease with reduced streamflow, as breeding of the colonially nesting water birds requires a certain minimum annual flow; climate change and reforestation can contribute equally to a decrease of river discharge, but before 2070 the largest impact can be expected from a shift in rainfall due to decadal-scale climate-variability (Herron, 2002). (Gooseff, 2005).

Climate change influences freshwater ecosystems not only via discharge quantities, but also water quality, in particular water temperature. For a temperature increase of 4.5 º C, considering five indices of thermal tolerance of fish a negative impact on trout population health and mortality in river in Montana, USA, was determined (Gooseff, 2005).

3.4.7 Water quality

From the observed effects of climate change and literature concerning future changes for some regions it is possible to identify future impacts and vulnerabilities on water quality. In lakes and reservoirs problems will arise due to higher water temperatures affecting stratification patterns, mixing regimes and dissolved compounds, particularly oxygen. These modifications will alter ecosystems (Lehman 2002; O'relly *et al.*, 2003; and Hurd *et al.* 2004). Higher temperatures are expected to transfer volatile and semi-volatile compounds (ammonia, mercury, PCBs, dioxins, pesticides) to the atmosphere (Schindler (2001) while, due to a water levels lowering, sediments from the bottom containing pollutants that affect biological communities and water supplies can be suspended (Lofgren *et al.*, 2002).

In regions where rainfall is expected to increase and be more frequent, pollutants (nitrogen, phosphorus, pesticides, organic matter, heavy metals, etc) will be washed from soils to water bodies (Atkinson *et al.*, 1999 and Fisher, 2000). The increase in nutrient loads in lakes and reservoirs will increase algae blooms altering ecosystems and affect water supplies with bad odour and taste (Moulton and Cuthber, 2000, Robarts *et al.*, 2005 and Interlandi and Crocket, 2003). Runoff can also increase acidification in rivers and lakes (Gilvear *et al.*, 2002). Spring can be a high runoff and pollution period because fertilizer and pesticide application combined with little vegetative cover increases vulnerability (Soil and Water Conservation Society, 2003; Atkinson *et al.*, 1999). Changes in water quality will have important deleterious effects, for instance in Lake Tanganyika, East Africa, that currently provides 25–40% of the animal protein supply for the populations of the surrounding countries, it is expected that climate change will reduce fish yields by approximately 30% (O'Rielly *et al.*, 2003). Sea-level rise and saline intrusion will pose a problem, more acute in coastal lagoons (Pittock, 2003 and Webster and Harris, 2004). Water quality modification could also be observed as result of more water impoundments to produce hydroelectricity, particularly in regions where this kind of energy is common (Polar regions, for instance Kennish, 2002).

Climate change will increase water temperature in rivers, hence ecosystems, mainly fish, will be affected negatively (Jallow *et al.*, 1999 and FAO 2003) or positively by enhancing productivity (Jallow *et al.*, 1999). As in lakes and reservoirs, more total rainfall and more frequent intense rainfall events (Leemans and Kleidon 2002) will induce soil fluvial erosion introducing in water suspended solids with a variety of compounds (Abler *et al.*, 2002; Atkinson *et al.*, 1999; Fisher, 2000; Mimikou *et al.,* 2000; Boursoui *et al.,* 2004; Walker, 2001; and Neff *et al.*, 2000). Since precipitation increase will occur in several parts of the world, pollution with sediments may be observed in several regions. In rivers next to the ocean and also on those where streamflow is expected to be reduced, salinity is expected to increase (Beare and Heaney, 2002; Bell *et al.*, and Heany, 2001; Robarts *et al.*, 2005 and Williams 2001)

From all water quality problems, the increase in groundwater salinisation may be the worst for water supply, due to the number of people relying only on aquifers and the certainty of the sea-level rise. Water salinisation is expected to be a major problem in coasts where larger evaporation rates will be present (Bobba *et al.,* 2000; Loáiciga's, 2003; US Country Studies Program, 1999; Han, *et al.*, 1999; Xu, 2003; Ministry for the Environment, 2002; CONAMA, 2004; Williams, 2001**;** Falkland, 2000; Todd, 2003) but also inland due to higher evapotranspiration (Chen *et al.*, 2004; Schmidt *et al.*, 2004). Other water quality problems are expected in aquifers due to increasing water withdrawals and a greater pollutant load during infiltration (GEO-LAC, 2003). Rising sea level can also disrupt storm water drainage operation and sewage disposal (Haines *et al.*, 2000).

Several studies predict that warmer temperatures and increased rainfall variability will increase the intensity and frequency of waterborne diseases. (Hall *et al*, 2002; D'Souza *et al*, 2004; Hijioka *et al.*, 2002), but predictions on how water quality in water supplies, drinking water and wastewater will evolve have not yet been done, although it is logical to expect (at least from the microbial point of view) that quality will deteriorate as a result of lower public health, mainly in developing countries. Climate change, as an additional variable, will make water quality and quantity differences between developed and developing countries even more disproportionate (Pachauri, 2004). Globally, poorer regions due to a minor capacity will be suffering more due to the impacts on water quality and quantity, the sea level rise, extreme weather events, food security, health risks from, and temperature-related morbidity in urban environments (Magadza, 2000). Climate change might affect the availability of safe water (WB, 2004) and compromise the fulfilment of the Millennium goals

Given the strong relation between biota and mean annual and summer temperatures in lakes in the polar regions (Korhola *et al.*, 2002; Ruhland *et al.*, 2003; Michelutti *et al.*, 2002; Wolfe and Perren, 2001) changes in water temperature will considerably impact ecosystem but with positive or negative effects (Wrona *et al.*, 2005), depending on the situation. Increments in nutrients and carbon loads in water will enhance productivity (Vincent and Hobbie, 2000), but sediment transport and greater nitrogen loads will alter ecosystems. For rivers in the polar regions, an increase in energy demand could induce the construction of more impoundments with effects on water quality (Prowse *et al.*, 2004).

By 2050, 15-20% of the world population may be living under water stress Arnell (2004). This will demand a more rational use of water, and certainly its reuse, particularly in those regions with an intensive use of water (more than 20 % of water use related to the renewable water resources). Water quality problems will need to be addressed in several regions in order to perform a safe reuse of water. Since agriculture is the activity demanding most water worldwide (70 % of the total amount, (WR, 2001), it is easy to fit wastewater quality to this use generally, it is convenience to recycle nutrients (Jimenez and Garduño, 2001) and the wastewater represents a reliable source (IWMI, 2003, Ensink *et al.*, 2004a and b), agricultural reuse will considerably increase.

3.4.8 Erosion

All of the studies to date on soil erosion suggest that increased rainfall amounts and intensities will lead to greater rates of erosion, and there appears to be little doubt that both average rainfall amounts and intensities are on the rise world-wide. Thus, erosion will also be on the increase, unless amelioration measures are taken. While soil erosion rates are expected to change in response to changes in climate for a variety of reasons, the most direct is the change in the erosive power of rainfall.

Nearing (2001) used output from the UK Hadley Centre model (HadCM3) and the Canadian Centre for Climate Modelling and Analysis model (CGCM1) and relationships developed by Renard and Freidmund (1994) between monthly precipitation and rainfall erosivity (the power of rain to cause soil erosion) to assess potential changes in rainfall erosivity in the United States. Predicted changes were significant and in many cases very large, but results between models differed both in magnitude and regional distributions. Zhang et al (2005) used output from HadCM3 and a relationship based on the literature data of Wang and Jiao (1996) to assess potential changes in rainfall erosivity in the Yellow River Basin of China. Increases in rainfall erosivity were projected across the region by as much as 11 to 22% by the year 2050.

Michael *et al.* (2005) projected potential increases in erosion on the order of 20 to 60% over the next five decades for two exemplary sites in Saxony, Germany. They used the erosion model EROSION 2D (Schmidt, 1990), and climate input data was based on regional downscaling methods of Enke (2000, 2003).

Pruski and Nearing (2002b) simulated erosion for the 21st century at eight locations in the United States using the Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995) modified for CO_2 effects on plant growth. Output from the UK Meteorological Office's Hadley Centre (HadCM3) was used for driving climate. The WEPP model incorporated all of the documented physical and biological mechanisms affecting erosion, including those listed above. Simulated cropping systems were corn and wheat. The results indicated a complex set of interactions between the several factors that affect the erosion process. Overall, these results suggested that where precipitation increases were projected, estimated erosion increased between 15 and 101%. Where precipitation decreases were projected by the GCM, the results were more complex due largely to interactions of plant biomass, runoff, and erosion, and either increases or decreases in overall erosion could occur.

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

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

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

3.4.9 Effects of climate-related changes in freshwater resources on sectors

Climate-related changes will have various impacts on freshwater demands of each sector. Basically, rise in temperature and decrease of precipitation will intensify water demands particularly for irrigation, and probably for urban water usage.

As results from a New York City study (Protopapas, *et al.*, 2000), precipitation typically causes a drop in water use in summer, hence change in the number of rainy days will have an impact of urban water use in the future. Joint statistics for temperature and water demand in New York City show that above 25^{o}C, water demand has a strong linear correlation with average daily temperature (with the slope of approximately 11 litres per day per person for a 1^{o}C rise).

For the Metropolitan area of Melborurne, water demand was found to be more sensitive to the precipitation and pan evaporation than to maximum temperature (Zhou *et al.*, 2000). The sensitivity of water consumption is approximately 9 litres per person per day for a 1^{o}C for lower temperatures and up to approximately 80 litres/p/d for a 1^{o}C rise above the threshold value of the maximum temperature (Zhou, 2001).

The decrease of spring runoff due to the reduction of snow accumulation and melting, and the decrease of summer runoff due to precipitation decrease will prolong the dry period, and will result in increasing irrigation requirements (Mimikou *et al.*, 1999). On the contrary, due to the combined effect of precipitation increase and shortening of the growing seasons, irrigation water will be reduced by 1-20 percent in 2021-2040 and by 17-51 percent in 2081-2099 although increases in temperature will cause increases in potential evapotranspiration of crops in the Southeast US (Hatch, *et al.*, 1999). The reduction in the water requirement will also be due to the increases in atmospheric CO_2 concentrations which have been shown to reduce crop water use due to increases in leaf stomatal resistance. For the US cornbelt, changes in crop water demand vary among regions depending on climate change scenario, decade, and crop, but the relative abundance of agriculture can be maintained under future climate change conditions (Strzepek, *et al.*, 1999). The significant decrease in transpiration and subsequent increase of runoff generation is reported from a numerical experiment with a hypothetic doubling of atmospheric CO_2 content by a dynamic global vegetation model (Gerten *et al.*, 2004), and it is likely that increase of CO_2 alone will reduce the irrigation demand and increase the available water resources. The effects of global change are on the whole likely to increase productivity of European agricultural systems, because increasing CO_2 concentration will directly increase resource use efficiencies of crops, and because warming will give more favourable conditions for crop production in Northern Europe (Olesen and Bindi, 2002).Water requirement by irrigated crops declines under these scenarios as transpiration is suppressed in US (Izaurralde *et al.*, 2003).

For China, climate change is expected to affect the agricultural water cycle, the agricultural water demand, potential for drought and surface runoff, and agricultural production. The rain-fed crops in the north China plain and northeast China would face water-related challenges in coming decades due to the expected increases in water demands and soil-moisture deficit, and decreases in precipitation (Tao *et al.*, 2003).

Hydroelectric production is affected by the change of river discharge regime, and it is also one of the impacts of climate-related change in freshwater resources. Decrease of minimum and annual mean runoff will increase the risk of failure to violate the corresponding constrains of energy production in Northern Greece (Mimikou *et al.*, 1999).

A summary of some key future impact and key vulnerability are evaluated and presented in Table 3.4.

Table 3.4: *Summary of future vulnerability for some hydrological events [it need to be completed and updated]*

Country or Region	Potential Hydrological Changes	Associated Concerns (Impacts)	Emissions Scenarios	Future Vulnerabilit y	Section
Many semi-arid and arid regions around the globe	Decrease of streamflow runoff	Lower water availability for humans and freshwater ecosystems Impacts in water availability	A1, A2, B1, B2	High	3.4.6
Colorado river basin	Decrease of streamflow	Impact in water demand	??	High— around 2020	

Yukon and coastal British Columbia (BC)	Increased spring flood risk in BC, impacts on river flows due to glacier retreat	Reduced hydroelectric potential	??	High [this is just an example]	
Western USA					
Humid	Rhine river basin the reduction in river discharge (may) be 5-12%	Navigation, water supply water for thermal power plant	???	Medium to Low for 2050	
Others (e.g., Hungary, Argentina, China & USA)	????	Impact on water for irrigation (maize & soybean yields)	???	Low for 2020 and 2050	
Southern Europe	Lower statistical low flows	Lower water availability for humans and freshwater ecosystems	A2	Medium for 2020s	3.4.6
North-eastern Brazil, south-western & southern Africa, southern rim of the Mediterranean Sea	Decrease in groundwater recharge	Lower water availability for humans and freshwater ecosystems???	A21 & B2	High for 2050s	3.4.4
Boreal, China and South Africa, Sahel, Near East, Australia, Western USA	Increase in groundwater recharge	???Soil salinization, problems in urban areas	A21 & B2	Low (this is just an example) High for 2050s	3.4.4
Southern Europe, Geer basin (??)	More frequent hydrological droughts Decrease in recharge	Lower water availability for humans and freshwater ecosystems???	IS92a, IPCC (???)	High for 2070s???	3.4.5

3.5 Costs and other socio-economic aspects

All impacts of climate change will entail social and economic costs and benefits. On top of the uncertainties in evaluating both climate change and potential impacts, evaluating the economic implications of the diverse impacts are fraught with additional difficulties, and few efforts to quantify them have been made. However, this section discusses the cost of adaptation in the water sector in relation to some water economy- related sectors such as irrigated agriculture, water supplies, insurance cost, building, infrastructure and owners lost in the case of floods.

Globally, economic losses due to natural catastrophes have increased seven-fold in the last 40 years, while insured losses have increased 14-fold (Annual review of natural catastrophes 2003, Munich Re Topics, 2004).

There have been a number of significant climate change-related extreme events in recent years. Small changes in the severity of extreme events (including water-related events: intensive storm, flood, drought, subsidence, etc) can result in higher increases in risk and in damage (amplification effect). On reasonable projections of extreme events, the pure risk rate for climate change related weather catastrophes is already rising at a rate of 2 - 4 % per year.

For instance, UK storm and flood losses in the period 1998 - 2003 have totalled 8.99 billion Euros, twice that of the previous period. Subsidence claims have not increased over the last 15 years, but annual costs vary considerably. There have been a number of significant water-related extreme events in recent years as follows:
- 1990 storms and coastal flooding in January and February led to 3.05 billion Euros in insurance claims, the highest figure for weather related claims to date. Over a 4-week period 3 million claims were received.
- 1995 following the hot, dry summer subsidence claims rise to 427.7 million Euros in 1995 and 482 million Euros in the following year. It is difficult to disentangle subsequent claims from other contributing factors, including dry conditions in 1997.
- 1998 Easter floods led to the evacuation of 1500 people from their homes, and a cost to the insurance industry of around 725 million Euros.
- 2000 the UK experienced its wettest autumn for almost 300 years, with heavy rainfall leading to damage of 10,000 properties, and nearly 1.45 billion Euros in insurance claims.
- 2003 the UK experienced its highest summer temperatures on record, leaving insurers with close to 580 million Euros in subsidence claims in that year alone.

(Association of British Insurers Statistics, date).

The underlying risk from extreme weather will continue to increase in the future, and very likely at an accelerated pace [High confidence].

Initial calculations suggest that future (2050) claim costs could be considerably higher than today's levels (cf. Table 3.5). These estimates ignore the effects of socio-economic changes, such as the location and value of assets, and any substantial changes in government policy.

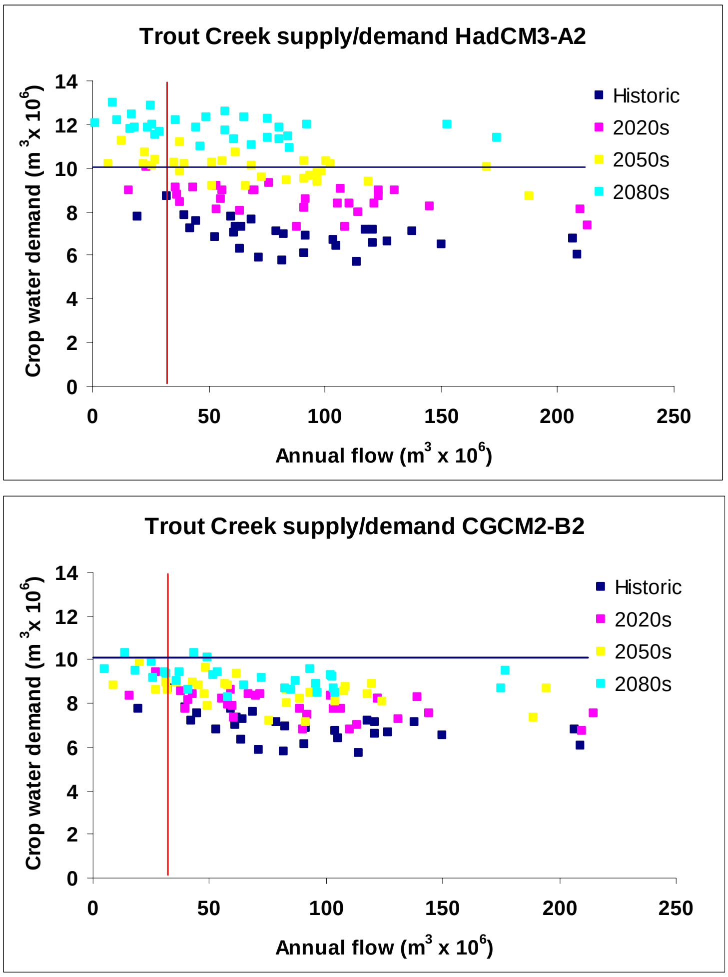
Table 3.5*: Preliminary estimates of future costs of weather insurance claims (converted from pounds to million Euros) (http://www.abi.org.uk)*

	Today		2050	
	Annual average	Extreme year	Annual average	Extreme year
Subsidence	435	870	870	1,740
Storm	580	3,625	1,160	10,875
Inland flood	580	2,175	1,160	6,525
Coastal floods	-	7,250	-	58,000
Total	1,595	13,920	3,190	77,140

Box 3.1: Water Management & Climate Change in Okanagan, Canada

The Okanagan region in British Columbia, Canada, is a semi-arid watershed of 8200 km^2 in area. The regional population is around 350,000, having nearly tripled since 1974. Agriculture, including extensive cultivation of fruits and horticulture, is highly dependent on irrigation. Irrigation accounts for approximately 78% of the total basin licensed water allocation. Water resources in the region are unable to support extension in demand.

Six GCM-based scenarios were assessed in this case study of the Okanagan region (Cohen *et al.*, 2004). Box 3.1 Figure 1 illustrates the worst case and least impact scenario changes in supply and demand for Trout Creek, compared with minimum (drought) supply thresholds and observed maximum demand. The drought threshold of 30.3 million m^3 (36% of average annual flow) has been proposed by local water authorities. During 1961-1990, there was only one occurrence in 30 years of modelled, unrestricted flow lower than the drought threshold, for a frequency of 3%. The demand threshold represents maximum observed demand using primarily trickle irrigation.



Box 3.1 Figure 1: *Scenario changes in water supply and demand for Trout Creek, Okanagan region, Canada. Minimum supply threshold is represented by the vertical line. Maximum observed demand is shown as the horizontal line. Of six scenarios used in this study, the upper panel shows the worst case, while the lower panel represents the smallest magnitude of impact (Neilsen et al., 2004).*

Estimates of demand varied among scenarios, with the most extreme responses occurring in the HadCM3-A2 scenarios, so that by the 2080s, demand exceeded the current observed maximum in every year. The CGCM2-B2 showed the smallest impact of the various scenarios. For all six scenarios, demand is expected to increase and supply is projected to decline. High risk outcomes to the Trout Creek system are defined as years in which demand exceeds 10.5 million m^3 and supply remains below the drought threshold of 30.3 million m^3. For HadCM3, high risk outcomes occur in 1 out of 6 years in the 2050s, and in 1 out of 3 year in the 2080s. Incidence of 'high risk' response for B2 scenarios was less than under A2.

Box 3.1 Table 1 illustrates the range of costs of adaptive measures that are currently available in the region. These costs are expressed by comparison with the least cost option, irrigation scheduling on large holdings, indicated as 1. The most expensive options per unit of water saved or stored are higher cost metering and lake pumping to higher elevations, each more than 5 times more expensive than the least cost option. No single option is expected to be sufficient. Rather, the various options could become part of a portfolio of measures (see other chapters in FAR)

Box 3.1 Table 1: *Relative comparison of costs per unit of water saved or supplied for demand side and supply side options in the Okanagan region, British Columbia (adapted from McNeill, 2004).*

		Relative Cost	Water saved or supplied
***Irrigation scheduling*:**	large holdings	1	10%
	small holdings	1.7	10%
Trickle irrigation:	high demand areas	3	30%
	medium demand areas	3.3	30%
Metering:	lowest cost	3.8	30%
	higher cost	4.6-5.4	20-30%
Public education:	large & medium communities	1.7	10%
Leak detection:	average	3.1	10-15%
Storage:	lowest cost	1.2	limited
	medium-high cost	2-3	limited
Lake pumping:	lowest cost	1.3	0-100%
	low cost (no balancing)	2.3	0-100%
	higher cost	4.4-5.4	0-100%

3.6 Adaptation: practices, options and constraints

This section aims to describe the range of options which can be used to adapt to changing climates. The IPCC TAR drew a distinction between "supply-side" and "demand-side" adaptation options, which is applicable to a range of systems. In this section an upgrade of options are included. Adaptation to extreme events (e.g., flood protection) are analyzed. Examples of supply-side and demand-side measures that are currently being considered in water management are presented.

Also, it discusses new developments in integrated water management – designed to manage water in a way that meets a range of demands and expectations. The case study "climate impacts on integrated water resources management of the Mbuluzi catchment in Swaziland" should be used as *an example of integrated water management under climate change. Adaptations options for this study would be indicated.*

This section describes factors affecting the ability of individuals, organisations, societies to adapt to changing circumstances, including the ability of individuals to alter demand for water-related services and whether there are limits to adaptation in the water sector, and seeks to identify case studies which have determined these limits.

Also, it discusses approaches which are or could be used to assist water resource decision making and describes practical example in different regions. Also, the section address the complementarity issue between adaptation and mitigation in the water sector.

This entire section aims to describe the range of options in the water sector which can be used to adapt to changing climates, practices in current adaptation (i.e., coping: handling present conditions) as well as the constraints (i.e., limit to adaptation)

Some technology options and practices

Technological developments may considerable affect the water resources and their management in a number of ways, depending on economic conditions, policy initiatives, and possible technology breakthroughs.

Water supply in water-scarce regions is expected to be supplemented increasingly by wastewater reuse, desalination, and long-distance transport across river basin boundaries. This additional water will likely be reserved for high value uses, such as household and industrial water use. In developing countries, a strong increase in pollutant emissions is expected, with wastewater treatment occurring only in some locations. In both developed and developing countries, diffuse emissions from farms will continue to be an important source of contamination.

One set of possibilities is focused on technologies to expand water supply sources for water-short regions. The most accessible options are water treatment, desalination, deep well pumping, and long-distance transport:

- Water treatment—especially re-use of waste water; technology applications to improve water quality as well as quantity (related to health and hygiene)
- Desalination—both from well water and seawaters- potential for large-scale conversion of seawater into fresh water; already in commercial use in some regions
- Deep well pumping—including applications of renewable energy in pumping (abundant wind power or geothermal energy)
- Long-distance water transfers.

It may be necessary to mix water from different quality regions in order to obtain a better quality blend. It is therefore necessary to develop water resources managements by considering regional variations in water quality. Şen *et al.* (2003) suggested an artificial mixture programs through simple management rules for groundwater resources in the central western parts of Saudi Arabia along the Red Sea coast where there is also saltwater intrusion into the unconfined aquifers.

A further set of possibilities is concerned with technologies to increase the efficiency of water use, which vary by sector. Current and continuing technology developments offer promise to increase the efficiency of water use in agriculture; in industry, including the energy sector (especially cooling); and in commercial and residential buildings.

Along with these technology potentials, technological development also offers improvements in water resource management through advances in sensors and controls.

Whether or not the potentials of many of these directions for technology development offer solutions to water supply and management problems of regions and sectors facing greater water scarcity due to climate change depends upon how adaptation strategies in the water sector are implemented in the light of climate change.

Technology is one of the tools than can help to control the effects of climate change on water quality. But it cannot solve all the problems related to its use. One example is salinity control. Even though membrane process can produce at a reasonably price freshwater for human consumption from a saline, source its use is prohibitively costly to desalinate water for agricultural purposes due to the high volumes required and the crops' low price. Thus other solutions must be sought such as an alternative technology, the use of crops resistant to salinity problems or economical tools (such as cross-financing between water sector users and responses to economical impacts from stakeholders, Abler, 2000).

Finally, along with technology, integrated water management (Luketina and Bender, 2001, Quinna *et al.*, 2001; Kashyap, 2004). must also cope with the effects of climate change regarding the relation between water quality, quantity, and uses. Such management should consider new actions when new effects are discovered or studied in more detail.

Adaptation to changing conditions in water availability and demand has always been the core of water management, although historically this has concentrated on changing demands for water: except where land use change is occurring, it has conventionally been assumed that the natural resource base is constant. Traditionally, hydrological design rules have been based on the assumption of stationary hydrology, tantamount to the principle that the Past is the key to the Future, which has a limited validity in the era of global change. If the stationarity assumption is not correct then the current procedures for designing water-related infrastructures have to be revised. Otherwise, systems would be over- or under-designed and might either not serve their purpose adequately, or be overly costly.

Flood defences

IPCC TAR drew a distinction between "supply-side" and "demand-side" adaptation options, which is applicable to a range of systems.

In flood protection, these two categories of adaptation options can be expressed as: either modify the floodwater, e. g. via water conveyance system ("take water away from the people") or modify the system's susceptibility to flood damage ("take people away from the water and reduce the loss potential"). There has been a significant shift from protective stance towards living with floods, as adequate protection may require unaffordable high expenditures. If a necessary level of protection cannot be provided and accommodation is not acceptable, a retreat could be a solution (Kundzewicz & Takeuchi, 1999): after the great 1993 flooding in the US, 20 thousand families have been relocated. However, this is not an ubiquitous remedy; there is no room to relocate millions of Dutch people living in flood-risk areas nor to relocate the tens of millions of Bangladeshis, populating two thirds of the total country area, which were under water during the 1998 flood.

Since flood risk tends to rise in many areas, increasing attention is being paid to upgrading flood protection systems. In order to improve flood preparedness, one has to select adequate site-specific measures, both structural ("hard"), defences such as dikes, dams and flood control reservoirs, diversions, etc, and non-structural ("soft") measures. The latter include watershed management (source control), i.e. modifying flood formation by "catching water where it falls". With certain practices of land use control and soil conservation, one can enhance water storage on the land surface or underground. Improved preparedness can be achieved by advance in awareness; information; therein flood forecasting–warning system; regulations, zoning; insurance. However, no flood protection measure guarantees perfect safety and complete protection. There is no single one-fits-all measure, hence a site-specific set of measures is advisable (Kundzewicz *et al.*, 2002).

The capacity of accommodation of flood impacts depends on the strength of economy. After a natural disaster, strong economies become strengthened and more effective by incorporating resilience, while weak economies are likely to be degraded. There is a clear, and intuitively expected, link between the wealth of the country and the value of the scalar flood loss index for extreme floods, defined as the ratio of material damage to the number of fatalities. The value of this ratio ranges from 20 thousand per fatality in a less developed country to 400 million USD in a developed country (Kundzewicz & Takeuchi, 1999).

Box 3.2: Lessons from the "Dialogue on Water and Climate"
(contributed by: Henk van Schaik, Jeroen Aerts, Ian Tellum and Phil O'Keefe)

"According to scientific reports climate is changing. Climate change affects the hydrological cycle and poses new challenges to preparedness and robust water governance. It is a matter of bearing in mind the relationship between water and climate. The Dialogue on Water and Climate is bringing climate and water scientists together with water managers and other stakeholders to learn how to better manage today's climate variability." ***His Royal Highness the Prince of Orange at the World Water Forum, Kyoto, March 2003***

Introduction

The Dialogue on Water and Climate (DWC) was launched in 2001 with the aim of raising awareness of climate implications for the water sector. The DWC initiated 18 stakeholder dialogues, at river basin, national and regional levels, 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. Eight of the 18 Dialogues were categorized as "Basin Dialogues" (Lena, Aral Sea, Yellow River, San Pedro, San Juan, Thukela, Murray-Darling, and Nagoya); two were "National Dialogues" (Netherlands and Bangladesh); the remaining eight were described as "Regional Dialogues" (Central America, Caribbean Islands, Small Valleys, West Africa, Southern Africa, Mediterranean, South Asia, Southeast Asia, Pacific Islands).

The Dialogues had their own objectives but all prepared a state-of-the-art report about water and climate. Some focused on model-based forecasting (e.g. Lena, Aral Sea), others on investigating local perceptions at village level (Bangladesh). Some brought together the science community and water managers (Murray-Darling, Thukela, San Pedro, West Africa). Others focused on NGOs (Small Valleys in Central America). The Netherlands Dialogue reported on experiences of current

Dutch water management that encompasses a broad cross sectoral concept of 'Living with Water', in which water is a principal determinant for spatial planning.

Results

The results have been substantive and the strong message going out of these Dialogues to governments, donors and disaster relief agencies is that it is on the ground, in the river basins and in the communities that adaptation actions have to be taken.

The Dialogues have shown that an integral approach is needed where vulnerability to climate change or climate variability and socio-economic development are considered. The Dialogues in Bangladesh and the Small Valleys in Central America have shown that villagers are well aware that climate extremes are becoming more frequent and more intense. The Dialogues also showed that adaptation actions in Bangladesh, the Netherlands, Nagoya, Murray-Darling, and Small Valleys are underway. In other areas, adaptation actions are in the planning stages (Western Africa, Mekong) and others are still in the initial awareness-raising stages (Southern Africa, Aral Sea, Lena Basin). A very positive outcome of the Dialogues in the small islands of the Caribbean and the Pacific is the Memorandum of Cooperation on Adaptation signed between the small islands during the World Water Forum 3. The results of the Dialogues are summarized in Kabat and van Schaik (2003) (http://waterandclimate.org). Presentation of results from the Dialogue can also be found in: Bergkamp *et al.* (2003). Aerts and Droogers (2004), Niasse *et al.* (2004), Hooijer *et al.* (2003), Browning-Aiken *et al.* (2004)

The Netherlands Climate Assistance Programme (NCAP) responds to the need of many developing countries to receive external technical and/or financial assistance to be able to adequately prepare, formulate, implement and evaluate national climate policy.

NCAP is supporting Bangladesh, Bhutan, Bolivia, Colombia, Ghana, Guatemala, Mali, Mongolia, Mozambique, Senegal, Suriname, Tanzania, Vietnam and Yemen to:

- Meet their commitments under the Climate Convention, in particularly the production of qualitatively good National Communications
- Give attention to impact and adaptation assessments, with particular attention to the consequences for the 'livelihood systems' of poor communities.
- Give attention to raising the awareness of climate change among policy makers, scientists, and relevant NGOs.

The NCAP has adopted a country-driven approach and the participating countries have chosen to focus on adaptation studies mainly in the area of water resource management and food security. There is also some attention to public health issues and to the role of pre-disaster planning in building national capacity to respond to climate change.

The NCAP aims to link the climate change agenda with national poverty alleviation plans, through a concentration on environmental change. The programme supports a 'people focused' approach rather than a primary focus on the physical events of climate change. As such, the focus of adaptation studies within the NCAP is on local livelihood systems and coping mechanisms that can be made more resilient and there is a strong emphasis on the dynamic and changing vulnerabilities of local populations.

Rather than merely supporting scientific data collection and analysis, the NCAP aims to support activities that are geared towards the formulation and implementation of climate policy. NCAP activities are therefore integrated into the respective governmental organizational structure and are usually based in the respective countries' Ministry of Environment, which ensures that NCAP activities may be coordinated closely with the NAPA. More information is available at www.nlcap.net.

Adaptation potential for implementation

The DWC demonstrated that the Dialogue model provides a successful mechanism for developing adaptation strategies with stakeholders. The next challenge is to implement adaptation policies. For this, the Dialogues raised two main options:

- Adaptation through mainstreaming within sectoral policies (water, disaster preparedness, agriculture, environment etc.) and
- Adaptation through the National Adaptation Plans of Action (NAPA)

Conclusions and recommendations

The DWC clearly demonstrated that a dialogue approach involving stakeholders supports identifying both climate threats and adaptation options. It also showed that climate change eventually will affect activities at all scales, and hence that adaptations should be identified in a multi-scale approach involving all levels of governance.

A variety of studies presented vulnerabilities and adaptations to climate change in water resources management. The challenge is to find both the resources and the institutional setting to implement adaptation policies. One option is to mainstream adaptation within sectoral policies, such as in water resources management. The challenge of mainstreaming is to:

- Raise the awareness of stakeholders that addressing adaptation in integrated water resources management can reduce vulnerability to climate change. Long-terms effects are, however, often not a high priority and a dedicated stakeholder process is a pre-requisite for successful development and implementation of adaptation policies.
- Search for options that enhance up-scaling local adaptations and local water management knowledge to the national scale and to fine-tune national policies to local scale activities.

3.6.1 Integrated water management strategies

This section discuss practices, new developments in integrated water management – designed to manage water in a way that meets a range of demands and expectations

Water-related problems are likely to become more severe, so improving efficiency of water management is indispensable. The environmental problems as well as the lack of water in the world have fostered an "integral approach" to water management. This concept increasingly includes more components as society realizes the role water plays for several activities as well as it discovers new interconnections between water and other resources. It means the technical, social, economic and political aspects of management of surface water and groundwater (quantity and quality) as a whole and, considering interactions with soil, atmosphere, flora and fauna. Also the time notion is considered and with it, the effects of climate change on the quantity and quality of water resources.

Water is a “fugitive” resource in the sense that it flows naturally from one place to another, from one reserve to another (e.g., surface to groundwater), and from one physical state (solid, liquid and gas) to another. Water has been defined as a property of territorial units in the legal setting, as a natural resource transformable into products for human consumption in an engineering setting, as a commodity that can be exchanged and traded between various places and various uses in an economic setting, and as a cultural resource (Blatter and Ingram, 2000). Strategic policy in the water sector has developed from supply oriented, through demand oriented to integrated approaches. Successful water management is crucial for the proper operation of natural environmental systems and for the support of human society. These two aspects are interdependent, but decisions about one are often made independently of the other. A persistent challenge is to consider these together in the context of a changing climate. Integrated water management is recognized as the appropriate framework to deal with complex water resources management issues, water management under uncertainty, and to articulate adaptive capacity as a significant feature of water management strategies. However the uncertainty and complexity of changes in the spatial and temporal distribution of rainfall, soil moisture, runoff, frequency and magnitudes of droughts and floods, have not been explicitly included in response planning (Stakhiv, 1999). This is slowly changing. However, systems design, operational inflexibility, and legal and institutional constraints reduce the adaptability of water systems and confound recommendations on responding to climate change. Developing countries are most vulnerable to climate-induced effects on water resources. While the biggest gaps in knowledge (e.g. ungauged basins) and drastic changes (e.g. in land-use) are found in these countries, they also have the lowest capacity for adaptation to change and are most vulnerable to increasing climatic risks.

White (1977) identified the major elements of integrated watershed development as follows: (1) multi-purpose storage reservoirs; (2) basin-wide planning; and (3) comprehensive regional development. However, decisions bringing rigidity to the management system may ultimately generate more problems than they resolve. A major implementation strategy, regionally and internationally, has been the integration of land and water resource planning under unified river basin administrations (cf. Table 3.4). Adaptive management is an approach to natural resources policy that recognizes a fundamental imperative: uncertainty is unavoidable in the interactions of society and environment; assessments of impacts and associated decisions are made across scales, and policies and their implementation. Learning from interventions in natural systems is needed to reduce uncertainty and to prepare for surprise or unintended consequences.

Most basins exhibit the characteristics of a "closed or closing" water system. In such systems, management of interdependence becomes a public function, and the development of mechanisms to allow resource users to acknowledge interdependence and to engage in negotiations and binding agreements on resource allocation becomes increasingly necessary. Multi-objective management is a tool used to optimize complex systems where there are multiple constraints, and provides a theoretical framework for decision-making (Schwartz, 2000). Measures undertaken include improvements in streamflow and demand forecasting, use of advance decision support systems, conjunctive water use models, monitoring of water supply and distribution, water-use efficiency technologies and public information communication and coordination. Unfortunately, water management decisions are often made under time and resource constraints. In addition, the approach focuses primarily on efficiency from an economic perspective and may not be able to accommodate other management objectives such as equity. Also in preliminary studies many managers and water agencies believe that they can withstand a repeat of past extreme climate patterns given current capacity, and that a significant adaptive response to change is not necessary.

Successful integrated water management strategies include: capturing society’s views; providing for participation; reshaping planning processes; coordinating land and water resources management; recognizing water source and water quality linkages; establishing protocols for integrated watershed management; addressing institutional challenges; protecting and restoring natural systems; reformulating existing projects; articulating risk; educating and communicating; linking technology and public policy; and emphasizing preventive measures. In addition successful integrated strategies explicitly address impediments to the flow of information across management and use nodes. Water managers have differing needs for scientific information relative to the scale of management, the type of decision being made, and the nature of the decision (e.g., long-term investments vs. short-term operational decisions). In the case of a large watershed such as the Colorado, these factors cross several time and space scales (Table 3.6). The challenge is to guide water management decision-making into flexible and environmentally sound directions.

Table 3.6: *Climate sensitive cross-scale issues in the integrated management of the Colorado River Basin ***(Pulwarty, reference?)****

Temporal scales	
Indeterminate:	Flows necessary to protect endangered species
Long-term:	Inter-basin allocations and allocations among basin states
Decade:	Upper Basin delivery obligations, life-cycle of humpback chub (*Gila cypha*)
Year:	Lake Powell fill obligations to achieve equalization with Lake Mead storage
Seasonal:	Peak heating and cooling months
Daily-monthly:	Flood control operations, Kanab Ambersnail impacts
Hourly:	Western Area Power Administration's power generation
Spatial scales	
Global:	Climate influences, Grand Canyon National Park World Heritage Site
National:	Western water development: irrigation, Grand Canyon Protection Act (1992)
Regional:	Prior appropriation, Upper Colorado River Commission, Upper and Lower Basin Agreements, energy grids
State:	Different agreements on water marketing within and out-of-state, water districts
Municipal, community, household	Watering schedules, treatment, domestic use

In international basins settings the lessons provided by the UN Convention on the Protection and Use of Transboundary Watercourses and International Lakes Convention and other agreements (Wieriks and Schulte-Leidig, 1997; Correia and da Silva, 1999) lead to the following conclusions: (1) international water problems can only be effectively handled on the river-basin scale with acknowledgement of interdependence; (2) river-basin management requires an integrated approach, including attention to ecological water quality and quantity issues; (3) international strategies and policies should leave room for flexible implementation; (4) public and political support are prerequisites for successful formulation, particularly regarding environmental policies; (5) major decisions cannot be taken without input from stakeholders and ensuring adequate legal basis for participation; and (6) cooperation requires mutual confidence among all parties involved.

Distinguish characteristics of developing and developed counties

Major differences exist in the way IWRM can be implemented between developed countries (DC) and less developed countries (LDC), cf. Table 3.7 (Schulze, 2001). Generally, DCs tend to focus more on quality of life, environment and on long-term issues while LCDs address more basic day-to-day issues (Schulze, 2001).

Table 3.7: *Characteristics influencing IWRM in more developed vs. less developed countries (after Schulze, 2001)*

INFRASTRUCTURE	
High level of infrastructural development with infrastructure generally improving	Infrastructure often fragile and frequently in a state of retrogression
Infrastructure decreases vulnerability to natural disasters (e.g. floods, drought)	High vulnerability to natural disasters; heavy damage and high death toll
High ethos of infrastructure maintenance	Low ethos of infrastructure maintenance
High quality data and information bases available, well co-ordinated	Data and information bases not always readily available
CAPACITY	
Scientific and administrative skills abundantly available	Limited scientific and administrative skills available
Expertise developed to local levels	Expertise highly centralised
Flexibility to adapt to technological advances	Often in survival mode; technological advances may pass by
ECONOMY	
Mixed, service driven economics buffered by diversity, highly complex interactions	High dependence on land, i.e. agricultural production; at mercy of vagaries of climate
Economically independent and sustainable	High dependence on donor aid, NGOs
Multiple planning options available	Fewer options available in planning
Take a long term planning perspective	Take a shorter term planning perspective
Countries wealthy, money available for planning and IWRM	Wealth of countries limited, less scope for planning and IWRM
SOCIO-POLITICS	
Population growth low or even negative	High population growth rates and demographic pressures on land
Generally well informed public with good appreciation of planning	Poorer informed public, less appreciation of science/planning
High political empowerment of stakeholders	Stakeholders often not empowered, afraid to act or to exert pressure

	Decision making centralised
Decision making decentralised	
ENVIRONMENTAL AWARENESS AND MANAGEMENT	
High level of expectation of planning and IWRM	Lower level of expectation and attainment of goals
Desire for aesthetic conservation	Need for basics for living

For many LDCs, beside changes in climate and its variability, there are many other stressors/problems they are facing, and depending on the magnitude of these changes, are often not viewed as the most pressing. This should be taken into account particularly when climate change is discussed in the context of LDCs. Also, the 'solutions' that come out of the discussions take the specific conditions of LDCs into account:

- Local catchment planning methodologies are both technically sound and participatory, building on local peoples' knowledge (i.e., vernacular knowledge), experience and practice.
- Planning initiatives are accessible to, and involve, local community organisations and include appropriate capacity building and technical support.
- The framework of initiatives encourages local-level collaboration amongst NGOs, CBOs (community-based organisations) and relevant government departments.

Box 3.3: Case study : Climate impacts on integrated water resources management of the Mbuluzi catchment in Swaziland

This case study recognizes that Integrated Water Resources Management in the Mbuluzi catchment in landlocked Swaziland is dominated by four issues:

- A high inter-annual variability of flow
- High levels of degradation due to overgrazing
- The huge Mnjoli Dam which supplies water for irrigation to over 20000 ha of sugar cane
- International water obligations to downstream Mozambique into which the Mbuluzi flows.

These issues pose substantial challenges to water management of the Mbuluzi catchment under conditions of climate change.

[The full development of this case study depends upon the more detailed research which is currently undertaken]

3.6.2 Autonomous actions vs. planned strategies

[This section will be developed depending on findings from the case study.]

3.6.3 Adaptive capacity

This section describes factors affecting the ability of individuals, organisations, societies to adapt to changing circumstances, including the ability of individuals to alter demand for water-related services

In general terms, there are three broad controls on adaptive capacity of units involved in managing water:

- sensitivity to change: how would climate change affect the provision of the water-related service (e.g. water supply or protection against floods);
- internal characteristics of the unit: wealth, education, access to knowledge etc;
- external conditions: e.g. role of regulators or the market.

Key importance of sensitivity to change and external conditions was shown for the UK water supply industry Arnell & Delaney (2004).

Among the most important social and structural elements of the adaptive capacity which can affect water demand (Mohieldeen, 1999) are such as: social and governance structures; infrastructure (e.g., transport and communication); knowledge base; and social capital (social resources).

3.6.4 Limits to adaptation

Adaptation in the water sector involves measures to alter hydrological characteristics to suit human demands and measures to alter demands to meet hydrological conditions. It is possible to identify four different types of limits on adaptation to changes in water quantity and quality. 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 financial limits to what is affordable. Third, there may be political or social limits to the implementation of adaptation measures. In many countries, for example, it is difficult for water supply agencies to construct new reservoirs, and it may be politically very difficult to adapt to reduced reliability of supplies by reducing standards of service. Finally, the capacity of water management agencies may act as a limit on which adaptation measures (if any) can be implemented. The low priority given to water management, lack of coordination between agencies, tensions between national and local scales, 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).

No studies have so far attempted to characterise or identify precisely such limits to adaptation, and most studies into real water management systems have just identified what adaptation might be necessary. For example, changes to flow regimes in California would “fundamentally alter California’s water rights system” (Hayhoe *et al.*, 2004), the changing seasonal distribution of flows across much of the United States would mean that “additional investment may be required” (Hurd *et al.*, 2004), changing streamflow regimes would “pose significant challenges” to the managers of the Columbia River (Mote *et al.*, 2003), and an increased frequency of flooding in southern Quebec would mean that “important management decisions will have to be taken” (Roy *et al.*, 2001).

A small number of studies have explored the physical feasibility and effectiveness of some specific adaptation options. Payne *et al.* (2004), for example, explored the effectiveness of three operational adaptations (plus a combination of the three) in the Columbia River basin against a number of criteria. They found that none of the options explored continued to meet all current demands, and that the balance between maintaining power production and maintaining instream flows for fish would have to be renegotiated: in other words, the climate change considered passed one limit. In a related study, Vanrheenen *et al.* (2004) examined the effect of different operational adaptations on the performance of the water supply system in the Sacramento-San Joaquin basin, California. As in the Columbia River, they concluded that "maintaining status quo system performance in the future would not be possible", without changes in demands or expectations. Neither of these studies considered the full range of adaptation options, including demand management or infrastructure developments.

The most comprehensive research into the feasibility of different adaptation options has been conducted in the Netherlands and the Rhine basin, with several key conclusions. First, the ability to protect against flooding depends on geographical context. It is feasible to provide enhanced protection against flooding in the Meuse basin, but not in the Rhine delta where virtually the entire floodplain is already protected by high dikes (Tol *et al.*, 2003). Second, it is very unlikely that it will be possible to manage flood levels in the Dutch portion of the Rhine through upstream measures (Middelkoop *et al.*, 2004), both due to physical limitations (land management actions would have little effect) and political limitations (upstream German communities are unlikely to support flood storage measures designed to protect downstream Dutch communities). Third, it is likely that only very radical flood management measures – such as the creation of a new flood overflow route for the River Rhine – would be able to reduce the physical flood risk to the Rhine delta in the Netherlands, and these would be extremely difficult politically to implement (Tol *et al.*, 2003).

Whilst there are no published examples of the consequences of passing future limits to adaptation, there is an increasing literature on the vulnerability of past resource-dependent societies to changes in water resource availability. The collapse of the Mayan civilisation in the 9th century, for example (Diamond, 2005), is partially attributed to changes in the availability of water, but vulnerability was determined largely by social and political conditions. The evidence from the past, therefore, is that the important limits to adaptation are those imposed not by the physical ability to adapt, but by the conditions under which adaptation takes place.

3.6.5 Uncertainty and risk: decision making under uncertainty

Climate change poses two major conceptual challenges to water managers. First, it means that it is no longer appropriate to assume that past hydrological conditions will continue into the future (the traditional assumption), and, second, that the future is uncertain. These together are likely to lead to changes in the procedures used to manage water resources and hazards. This 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 impacts assessments have used just a small number of scenarios. These have demonstrated that impacts vary between scenarios, although temperature-based impacts, such as changing in the timing of streamflows, tend to be more robust (Maurer &

Duffy, 2005), and the use of a scenario-based approach to water management in the face of climate change is therefore widely recommended (e.g. Beuhler (2003), Simonovic & Li (2003), McIntyre *et al.* (2003)). There are, however, two problems. First, the large range frequently simulated between different climate model-based scenarios suggests that adaptive planning should not be based on only a few scenarios (Prudhomme *et al.*, 2003): there is no guarantee that the range simulated represents the full range. Second, it is difficult to evaluate the credibility to give to individual scenarios. By making assumptions about the probability distributions of the different drivers of climate change, however, it is possible in principle to construct probability distributions of hydrological outcomes, although the resulting probability distributions will be influenced to a degree by the assumed initial probability distributions. Maheelpa & Perera (2003), for example, developed a method using probability distributions of input drivers to place confidence levels on the plausible values of measures of system performance, and demonstrated the method for a water supply system in Australia. Jones & Page (2001) constructed probability distributions for water storage, environmental flows and irrigation allocations in the Macquarie River catchment, Australia, showing that the estimated distributions were in fact little affected by assumptions about probability distributions of drivers of change.

Water managers in several countries 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), and methods are under review following the publication of new scenarios (Hawkes *et al.*, 2003). Water supply companies in England and Wales used four climate scenarios in their 2004 review of future resource requirements, using a formalised procedure developed by the environmental and economic regulators (Arnell & Delaney, 2005). This procedure basically involved the companies estimating when climate change might impact upon reliability of supply, and undertaking different actions depending on when these impacts would be felt (in most cases estimated effects were too far into the future to cause any changes in practice now, but in some instances the impacts would be soon enough to necessitate undertaking more detailed investigations now). Dessai *et al.* (2005) describe an example where water supply managers in Australia were given information on the likelihood of drought conditions continuing, under different assumptions about the magnitude of climate change. They used this information to decide on whether to invoke contingency plans to add temporary supplies or tighten restrictions on water use.

A rather different way of coping with the uncertainty associated with estimates of future climate change on hydrological and water resources characteristics is to adopt management measures which are robust to uncertainty. Integrated Water Resources Management (cf. 3.6), 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, for example (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" strategies in the face of uncertainty (Klijn *et al.*, 2004).

3.7 Implications for sustainable development

This section would try to summarize the key projected impacts in a single matrix (as recommended by the TSU) covering three time slices and two or more different development contexts (which may be characterized by varying vulnerabilities measures, or SRES future, or form of governance.

Since the turn of millennium, water management agencies in many countries have embraced the concept of "sustainable management" or "sustainable development" of water resources (see Clark, 2002; Harman *et al.*, 2002; Loucks *et al.*, 2000; Ming, 2003; Carroll, 2003 for examples). Climate change is frequently cited as one of the drivers encouraging more sustainable use of resources and ways of coping with water-related hazards (e.g. Mitchell, 1999; Crookall & Bradford, 2000; Kent *et al.*, 2002; Carroll, 2003; Kundzewicz, 2002; Kashyap, 2004).

The precise interpretation of "sustainable" water resources management, however, varies considerably. All definitions broadly include the concept of maintaining and enhancing the environment, but interpretations of "environment" vary. All refer explicitly to the need to protect and enhance the water environment, taking into account competing users, instream ecosystems and wetlands (e.g. Franks *et al.*, 2004). Few, however, consider the wider environmental implications of water management policies, such as implications for land management, or the implications of land management policies for the water environment (Carter *et al.*, 2005). Few also take into account the energy implications of water management (desalination, for example, has been proposed as a sustainable water management measure (Boutkan & Stikker, 2004), even though it uses large amounts of energy). However, many water management actions and adaptations, particularly those involving pumping or treating water, are very energy intensive. Their implementation would affect energy emissions, and energy policy could affect their implementation (Mata & Budhooram, 2004).

Most interpretations of sustainability assume economic as well as environmental sustainability (particularly where water management is in the private sector), but few definitions refer explicitly to the social sustainability of water management actions. However, equity in impact of an adaptation action is a key aspect of sustainability and effectiveness of adaptation (Adger *et al.*, 2005). Examples of potential inequities occur where people benefit differently from an adaptation option (such as publicly-funded flood protection) or where people are displaced or otherwise adversely impacted in order to implement an adaptation option (such as a new reservoir) (*give examples*).

Since 2000, many decision-support tools have been proposed to aid the sustainable management of water resources (e.g. Mitchell, 1999; Zacharias *et al.*, 2003; Ochola *et al.*, 2004; Guo *et al.*, 2004; Fassio *et al.*, 2005). Few, however, have explicitly incorporated climate change (Kashyap, 2004).

[Placeholder for some examples such as Rural water supplies and sustainability Millennium development goals]

3.8 Key uncertainties and research priorities

The section should summarize uncertainties presented along the chapter and whenever is possible to present confidence levels; also it should address the research gaps and priorities.

[This section will be truly developed later on, during the Second Order Draft process]

There are strong uncertainties in quantitative projections of changes in hydrological characteristics for a drainage basin, the basic unit of water management. Precipitation, the principal input signal to water systems is not reliably simulated in present climate models, so the projections are highly model-dependent. This has two implications. First, adaptation procedures need to be developed, which do not rely on precise projections of changes in river discharge, groundwater, etc. Second, based on the studies done so far, it is difficult to assess water-related consequences of climate policies and emission pathways with high reliability.

Integrated water management , necessary for solving increasingly complex water problems, must be extended to include the effects of climate change. Whereas it is difficult to make concrete projections; it is known that hydrological characteristics will change in the future. Water managers in some countries (e.g. flood management and water supply management in the UK) are already considering explicitly how to incorporate the potential effects of climate change into policies and specific designs.

Add - Detection and attribution of changes.

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