# Chapter 3. Freshwater Resources

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## Contents

## Executive Summary

[to come]

## 3.1. Introduction

All organisms, including humans, require water for their survival. Therefore, ensuring that adequate supplies of water are available is essential for human well-being (Oki and Kanae, 2006), and any changes in the climate system and hydrological cycles on the Earth has a potential to increase the risks of water-related hazards, such as storm surges, floods, debris flows, and droughts as schematically illustrated in Figure 3-1 (currently from MLIT, 2008, but will be newly developed later), and demand the changes for human society in the way how to manage water resources. Even though water is circulating on the Earth and water resources are renewable, water is a localized resource, and the sensitivity of hydrological changes to climate change and the vulnerabilities to water-related hazards are diverse in each region.

[INSERT FIGURE 3-1 HERE
Figure 3-1: This is an example figure and Ch3 Author Team will develop a new figure illustrating the framework.]

Anthropogenic climate change is one of the multiple stressors on water sector. Non-climatic drivers such as population increase, concentration to urban area, and economic developments, have also challenged the sustainable water resources management through increasing the demand or decreasing the available freshwater resources by deteriorating water quality. In this sense, adaptation options to climate change in water sector can be learned from historical experiences how human beings overcame the water issues caused by non-climatic drivers and non-human induced climate changes.

In the Working Group II Fourth Assessment Report (AR4; IPCC, 2007), the state of knowledge of climate change impacts on hydrological cycles and water resources managements was presented in the light of literature up to the year 2006 (Kundzewicz *et al*., 2007). Key messages with very high confidence or high confidence are:

- The impacts of climate change on freshwater systems and their management are mainly due to the observed and projected increases in temperature and sea level, local increases or decreases of precipitation, and to changes in the variability of those quantities.
- Semi-arid and arid areas are particularly exposed to the impacts of climate change on freshwater.
- Higher water temperatures, increased precipitation intensity, and longer periods of low flows exacerbate many forms of water pollution, with impacts on ecosystems, human health, water services systems reliability and operating costs.
- Climate change affects the function and operation of existing water infrastructure as well as water management practices.
- Adaptation procedures and risk management practices for the water sector are being developed in some countries and regions (e.g., Australia, Caribbean, Canada, Germany Netherlands, UK, USA,) that have recognized projected hydrological changes with related uncertainties.
- The negative impacts of climate change on freshwater systems outweigh its benefits.

This chapter gives an overview of observed (Section 3.2) and future impacts (Section 3.4) of climate change on freshwater resources and their management, mainly based on research published after the Fourth Assessment Report. Socio-economic aspects (Section 3.3), the impacts, vulnerabilities, and risks for human and environmental systems (Section 3.5), adaptation issues (Section 3.6), implications for sustainable development (Section 3.8), as well as uncertainties and research priorities, are also covered. The focus is on terrestrial water in liquid form, due to its importance for freshwater use and management, and linkages with other sector are described in Section 3.7. The current gaps in research and data when assessing the impacts are summarized in Section 3.9. Please refer to the Working Group I Fifth Assessment Report (Stocker *et al*., 2013): to Chapter 2 for further information on observed trends, to Chapter 4 for freshwater in cold regions, to Chapter 10, 11, and 12 for detection, attribution, and projection of climate change, and to Chapter 14 for extremes. While the impacts on aquatic ecosystems are discussed in this volume in Chapter 4, findings with respect to the effect of changed flow conditions on aquatic ecosystems are presented here in Section 3.5.5. While Chapter 7 describes the overall impacts of climate change on food production, Section 3.5.2 briefly summarizes the implication of hydrological changes by climate change on the agricultural sector. The health effects of changes in water quality and quantity are covered in Chapter 11, while regional vulnerabilities related to freshwater are discussed in Chapters 21–30.

## 3.2. Observed Impacts, with Detection and Attribution

### *3.2.1. Precipitation (Rainfall and Snowfall), Evapotranspiration, Soil Moisture and Permafrost, and Glaciers*

Changes in global precipitation are observed and simulated by multiple General Circulation Models GCM (Lambert and Allen, 2009; IPCC AR4 WGI, 2007), but global trends cannot be determined (Lambert and Allen, 2009). Linear trends for global averages from different datasets (e.g. GHCN, GPCP, GPCC, PREC/L, CRU, etc) during 1901–2005 are statistically insignificant (Bates *et al*., 2008). Climate models appear to underestimate the variance of land mean precipitation compared to observational estimates (Bates *et al*., 2008). In recent years, the worst droughts and extreme rainfall events in more than the last five decades were identified in regional observational data (Arndt *et al*., 2010). Certain trends in total precipitation and precipitation extremes are observed, for example in South China where increases in dry days and a prolongation of dry periods have been detected (Gemmer *et al*., 2011; Fischer *et al*., 2011).

It is assumed that the water-holding capacity of the atmosphere and evaporation into the atmosphere increase with higher temperatures (IPCC AR4 WGI, 2007). This favors increases in climate variability, with more intense precipitation and more drought events (Trenberth *et al*., 2003; Bates *et al*., 2008).

Trend estimations for global evapotranspiration are still not compelling due to high uncertainties in global research results. There is still little literature on observed trends in evapotranspiration, whether actual or potential (Bates *et al*., 2008). On a global scale, evaporation increased from the early 1980s up to the late 1990s but not thereafter, although the reason appears to be drying of land surfaces and not reduction of atmospheric evaporative demand (Jung *et al*., 2010).

Few long-term records of soil moisture content are mostly available for the former Soviet Union, China, and central USA (Bates *et al*., 2008; Wang *et al*., 2011). Robock *et al*. (2005) observed an increasing long-term trend in soil moisture content during summer for stations with the longest records. Common approaches to simulate soil moisture have been for example remote sensing techniques, the Palmer Drought Severity Index (PDSI), as well as various land surface hydrology models which both are based on observed meteorological data (Sheffield and Wood, 2007; Wang *et al*., 2011). With such methods, regional down and upward trends in soil moisture have been calculated for China, where the trend to more severe soil moisture droughts has been experienced (Wang *et al*., 2011).

An overall decrease in areas under permafrost and a retreat of glaciers is observed. On average, glaciers and ice caps in the Northern Hemisphere and Patagonia show substantial increases in melting (IPCC AR4 WGI, 2007; Bates *et al*., 2008). It is *virtually certain* that mass loss from glaciers and ice caps has contributed to observed sea-level rise (Bates *et al*., 2008), and *very likely* that the ice sheets are making a substantial and growing contribution (to be updated ZOD of WGI). Observed trends are partly explained by external forcing, which in turn shows an increasing anthropogenic signal (Stroeve *et al*., 2007; Min *et al*., 2008)). As an example, fast glacier margin recession, thinning of the ice cover, elevation of the regional snowline, and the reduction of Andean areas under permafrost conditions are predicted for South America (Rabassa, 2009). [to be updated when AR5 WGI results are available]

Changes in precipitation are attributed mainly to warming of the atmosphere which causes changes in circulation characteristics (Lambert *et al*., 2004; Stott *et al*., 2010). Regarding the human influences on precipitation changes, it is found that precipitation responds more strongly to anthropogenic and volcanic sulfate aerosol and solar forcing than to greenhouse gas and black carbon aerosol forcing (Lambert and Allen, 2009). Climate models suggest that anthropogenic forcing should have caused a small increase in global mean precipitation, while it is estimated that anthropogenic forcing contributed significantly to observed increases in precipitation in the Northern Hemisphere mid-latitudes, drying in the Northern Hemisphere subtropics and tropics, and moistening in the Southern Hemisphere subtropics and deep tropics (Zhang *et al*., 2007).

### *3.2.2. Runoff and Stream Flow (including Seasonal Snow Cover and Snow Melt), Floods and Droughts*

Consistent global and regional changes of runoff and stream flow are difficult to detect due to limited geographical coverage of gauge stations, short time series, incomplete records and intensive modification of natural stream flow volumes. The AR4 described with regional changes on stream flow volumes (Trenberth et al., 2007), including an increase in flow in many parts of USA (Groisman et al., 2004), in Eurasian Arctic rivers (Yang et al., 2002) and southeastern South America (Genta et al., 1998), together with a decrease over many Canadian Rivers (Zhang et al., 2001b).

Recent analysis of streamflow records have detected spatial and temporal changes in stream flow mainly attributed to changes in seasonal rainfall distribution. Stahl *et al*. (2010) investigated streamflow data across Europe and found negative trends (lower streamflow) in southern and eastern regions, and generally positive trends (higher streamflow) elsewhere (especially in northern latitudes). In the Nordic countries, the overall picture shows a trend towards increased streamflow annual values in particular during winter and spring seasons (Wilson *et al*., 2010). In the USA, a significant statistical increasing trend of streamflow was detected for the Mississippi and Missouri regions, whereas a decreasing trend was found for the Pacific Northwest and South Atlantic-Gulf regions (Kalra *et al*., 2008). Analysis of global discharges based on model-simulated runoff ratio during 1948-2004 (Dai et al., 2009) revealed that only about one-third of the top 200 rivers (including the Congo, Mississippi, Yenisei, Paraná, Ganges, Columbia, Uruguay, and Niger) showed statistically significant trends, namely 45 rivers recording downward trends and only 19 having an upward discharge trend. According to Dai *et al*. (2009), global discharge data show small or downward trends, which are statistically significant for the Pacific.

Changes on seasonal rate of streamflow are more evident where seasonal snow storage and melting plays a significant role in annual runoff (Trenberth *et al*., 2007). As mean winter temperature increase, there is more winter precipitation falling as rain instead of snow, together with an earlier timing of snowmelt-driven streamflows in spring. This has been observed in the western U.S. since 1950 (Regonda *et al.,* 2005; Barnett *et al.,* 2008; Hidalgo *et al.,* 2009; Clow, 2010) and in Canada (Zhang *et al.,* 2001), along with an earlier breakup of river ice in Russian Arctic rivers (Smith*,* 2000). There is no significant evidence identified on how global warming has affected the magnitude of the snowmelt flow peak (Cunderlik and Ouarda 2009). It is expected that projected warming may result either in an increase in spring flood peak, where winter snow depth increases (Meehl *et al.,* 2007b), or a decrease in spring flood peak in regions with decreased snow cover and amounts (Hirabayashi *et al.,* 2008b; Dankers and Feyen*,* 2009). In regions where the lowest mean monthly flow occurs in summer, streamflow has experienced a relative decreases in discharge volume exacerbating drier summer conditions (Knowles *et al*., 2006; Cayan *et al*., 2001).

*Floods*

The AR4 concluded that no gauge-based evidence had been found for climate-related trend in the magnitude/frequency of floods during the last decades (Rosenzweig *et al.,* 2007), while an increase in heavy precipitation events was already *"likely"* in the late 20th century trend (Trenberth *et al.,* 2007). Reported flood disasters and damages worldwide have been increasing since 1970s (Kundzewicz *et al.,* 2007), although this increase may be explained in terms of higher exposure and vulnerability of assets (SREX report, chapter 4). Cunderlik and Ouarda, (2009) reported a change on flood frequency on snowmelt floods (earlier snowmelt) being negative in SE Canada, and positive in NW Canada, with a 20% of stations showing a decrease magnitude of annual maximum floods due to snowmelt over the last three decades. In contrast, there is no evidence of widespread trends in extreme floods based on daily river discharge of 139 Russian gauge stations (Shiklomanov *et al*., 2007). Similarly, statistical analysis of annual maximum stream flows in the USA at 30-yr (1959-1988) and 50-yr (1939-1988) timeframes do not prove any significant trend (Douglas *et al*., 2000) probably showing the inability to detect any trend based on short term flow series.

In Europe, significant upward trends in floods are detected for river basins in W, S and central Germany for the period 1951-2002 (Petrow and Merz, 2009), in agreement with the increasing trend in annual and winter flood discharges since 1984 in the Meuse river (NW Germany, The Netherlands and Belgium) and its tributaries (except Geul River, Tu *et al*., 2005). In contrast, in E and NE Germany and in the Czech Republic (Elbe and Oder rivers), a slight decrease in winter floods and no change in summer maximum flow was reported (Mudelsee *et al*., 2003). In France, there is no evidence on generalized trend on annual flow maxima, although regional discrimination show a flood frequency trend to decrease in the Pyrenees, a flood magnitude decrease in the Alps region, in relation with earlier snowmelt processes, and increasing annual maxima flows in NE region (Renard *et al*., 2008). In Spain, southern Atlantic catchments (Guadalquivir and Guadiana) showed a decreasing trend in flood magnitude and frequency, whereas in central and northern Atlantic basins (Tagus andDouro) no significant trend in frequency and magnitude of large floods is observed (Benito *et al*., 2005). Flood records from a network of catchments in the UK showed significant positive trends in high-flows indicators primarily in maritime-influenced, upland catchments in the north and west of the UK (Hannaford and Marsh, 2008), although in previous studies those changes were not so obvious (Robson *et al*., 1998).

In Asia, flood discharge of the lower Yangtze region shows an upward trend in the last 40 years (Jiang *et al*., 2008), and both upward and downward trends were identified in a 40-yr record of four selected river basins of the northwestern Himalaya (Bhutiyani *et al*., 2008). In the Amazon region, large floods have been registered in the main channel of the Amazon river and its tributaries, including the July 2009 flood considered one of the highest in 106 years of record of the Rio Negro at Manaus (Marengo*,* 2011).In Africa, there is no evidence of flood magnitude changes during the 20th Century, probably due to limited long and complete streamflow datasets (Conway *et al*., 2009). Di Baldassarre *et al*. (2010) have attributed the increase in flood fatalities in Africa to intensive and unplanned human settlements in flood-prone areas.

Several studies (Pall *et al*., 2011, Min *et al*., 2011) combining observations with model results forced with anthropogenic and natural drivers have concluded that anthropogenic greenhouse gas emissions have increased the risk of floods and extreme precipitation in different regions of the northern Hemisphere. Although attribution of particular flood is difficult, these studies show higher probability of extreme rainfall events is attributed to anthropogenic climate change.

*Droughts*
Using the PDSI, Dai *et al*. (2004) found that very dry areas (PDSI < -3) in the World had augmented in its extent from 12 to 30% since 1970s. It is very likely that this trend in the PDSI proxy is largely affected by the anthropogenic increase in temperature, whereas regional differences in precipitation patterns (seasonal and inter-annual) introduce the spatial and temporal drought variability and their impacts at local scales (refer to AR5 regional chapters).

Beniston (2009) used joint temperature-precipitation quantile exceedance analysis in nine European stations over the $20^{th}$ C, pointing out towards a strong increase in warm-dry mode over central-southern countries. In the U.S., droughts are becoming more severe in some regions, but there are no clear trends for North America as a whole (Kunkel *et al.,* 2008; Wang *et al.,* 2009). In South America analyses of the instrumental and reconstructed precipitation series indicate that the probability of drought has increased during the late $19^{th}$ and $20^{th}$ centuries (Le Quesne *et al*., 2006; 2009). For the Amazon, repeated strong droughts have been occurring in the last decades but no particular trend has been reported (SREX Chapter 3). Changes in drought patterns have been reported for the monsoon regions of Asia and Africa with variations at the decadal timescale (e.g., Janicot, 2009). In the Sahel, a region characterised by frequent droughts, recent years have recorded a greater interannual variability than the previous 40 years (Ali and Lebel, 2009; Greene *et al*., 2009), and by a contrast between the western Sahel remaining dry and the eastern Sahel returning to wetter conditions (Ali and Lebel, 2009). Giannini *et al*., (2008) report a drying of the monsoon regions, related to warming of the tropical oceans, and variability related to the El Niño–Southern Oscillation.

In general terms, the SREX Chapter report (2012) concluded that there is *medium confidence* that since the 1950s some regions of the world have experienced more intense and longer droughts (e.g. southern Europe, West Africa, East Asia) but also opposite trends exist in other regions (e.g. Central North America, Northwestern Australia). Modeling of meteorological droughts in the Hadley CGM model showed a global drying trend in PDSI values attributed to anthropogenic emissions of greenhouse gasses and sulphate aerosols (Burke *et al*., 2006).

### *3.2.3. Groundwater*

Observed changes in groundwater level and storage are largely attributable to human water withdrawals and other human actions not related to climate change. Attribution of groundwater changes to climatic changes is rare. Observed decline of the discharges of karst and other springs in Kashmir (India), and thus of groundwater recharge, was 40-70% during 1981-2005, and it was attributed to decreased precipitation during the snow accumulation period and to glacier disappearance (Jeelani, 2008). The temporal development of groundwater recharge during the $20^{th}$ century in four overexploited karst aquifers in SE Spain was studied by calibrating a model to observed groundwater head during a period of approx. 10 years, using information on groundwater withdrawals during this time. In all four aquifers, modelled groundwater recharge decreased logarithmically during the $20^{th}$ century, and the percentages of groundwater recharge with respect to total (declining) precipitation declined approximately linearly, indicating the effect of temperature-induced increase of evapotranspiration during the $20^{th}$ century on renewable groundwater resources (Aguilera and Murillo, 2009).

### *3.2.4. Water Quality*

Currently, little information is available with regard to observed changes in water quality that are caused by climate change. In addition, when they are available such reports generally refer only to surface water bodies. In general, studies show historical data linking water quality to changes in temperature and/or precipitation or to unusually warm conditions, extreme events, climate variations, the ENSO phenomenon, and rises in sea level. Indirect effects of climate through changes in land use have also been reported (Pednekar *et al*., 2005; Paerl *et al*., 2006; Tibby and Tiller, 2007; Coats 2008; VanVliet and Zwolsman, 2008; Qin *et al*., 2010; Bonte and Zwolsman, 2010; Benítez-Gilabert *et al*., 2010; Sahoo *et al*., 2010; Tetzlaff *et al*., 2010; Marce *et al*., 2010; Saarinen *et al*., 2010; Ventela *et al*. 201; Emelko *et al*., 2011) .

For lakes, reservoirs, bays and estuaries the main impacts reported were on water temperature, nutrient content, salinity and levels of faecal pollution (Pednekar *et al*., 2005:Paerl *et al*., 2006;Tibby and Tiller, 2007; Qin *et al*., 2009; Bonte and Zwolsman, 2010; Sahoo *et al*., 2010). Eutrophication, as result of a higher nutrient content, seems to be a major problem, often impairing drinking water quality due to algal blooms linked this too to water temperatures (Sahoo *et al*., 2010; Qin *et al*., 2010; Trolle *et al*. 2011). In reservoirs used to manage water supply, stream flow variations were of greater significance than temperature increases in the depletion of dissolved oxygen (Marce *et al*., 2010). One positive impact observed was the effect of large storms and hurricanes in flushing previously deposited and stored nutrients from wetlands and swamps (Bales 2003; Paerl *et al*., 2006). In rivers, the variations observed (Evans *et al*., 2005; Brown *et al*., 2007; Saarinen *et al*., 2010; Benítez-Gilabert *et al*., 2010; Gascuel-Odoux *et al*., 2011; Tetzlaff *et al*., 2010) were in terms of water temperature and the levels of sediment, organic matter, pathogens, conductivity, nutrients and acidity (for some Nordic regions) contents. Most studies were carried out in developed countries reporting as a major pollutant the increase in organic matter in drinking water supplies linked to an increased precipitation and other non-climatic drivers (Evans *et al*., 2005). In streams in semiarid areas temperature changes were more important than precipitation in terms of their effect on the content of organic matter, nitrates and phosphorus (Ozaki *et al*. 2003; Chang 2004; Arheimer *et al*. 2005; Benítez-Gilabert *et al*. (2010). With regard to pathogens, observations made during wet periods consistently showed an increased rate of pollution. However during dry periods levels of pollution were extremely variable, illustrating the need for a better understanding of this phenomenon (Tetzlaff *et al*., 2010). Wild fires attributed to climate change (Westerling *et al*., 2006; Flannigan *et al*., 2005) had a significant impact on turbidity, dissolved organic matter and the content of heavy m*et al*.s in water up to 4 years later, resulting in an increase in treatment costs and a reduction in the reliability of the supply (Emelko *et al*., 2011).

Some general conclusions are (Evans *et al*., 2005; Senhorst and Zwolsman, 2005; Gascuel-Odoux *et al*., 2011; Saarinen *et al*., 2010; Benítez-Gilabert *et al*., 2010; Kundzewicz and Krysanova 2010; Tetzlaff *et al*., 2010; Ventela *et al*., 2011): (a) results should be interpreted cautiously as a complex interrelationship exists between climate, hydrology, natural conditions and management practices in determining the impact of climate change on water quality; (b) the relationship between water quality and climatic parameters is non-linear, dynamic and difficult to distinguish from other natural and anthropogenic drivers; (c) there is a need to fully understand what the ‘‘reference’’ state of water systems is, since they may have been impacted upon for a considerable time and for several reasons; (d) if observed trends continue, the measures already in place to control point and non-point sources of pollution will be insufficient to deal with the negative impacts of climate. This applies particularly to those created by nutrient loads in places already suffering from eutrophication due to soil erosion, intensive farming practices, and/or municipal and industrial pollution.

### *3.2.5. Sediment Load, Soil Erosion (including Land Slide)*

The potential for global climate changes to increase the risk of soil erosion is clear, but the actual damage is difficult to estimate. There are two ways in which soil erosion and sediment production may be affected by climate change: (1) change in seasonal rainfall distribution, and (2) change in rainfall extremes. Changes in seasonal distribution of rainfall have been described in different world regions, with higher winter and early spring rainfall amounts, at times of low soil protection in agricultural fields. Moreover, increase in rainfall extremes is likely to contribute to higher erosion rates.

### *3.2.6. Water Use and Availability*

In relation to drought risks, a global increase in water demand has exacerbated dry conditions and desertification of vulnerable areas in Africa and Asia (Dregne, 1986; Aggerwal and Singh, 2010).

[This section will be fed by an assessment of trends, detections and attributions of climatic changes on water use and availability in the past.]

### *3.2.7. Water Management*

Reported water-related Disaster Events recorded globally (1980 to 2006) shows an increase on the number of droughts with significant socio-economic impacts (Adikari and Yoshitani, 2009). As many water management systems in low rainfall areas (200-500 mm) are in the limit of supply reliability, small reductions in rainfall due to climate change may pose at risks up to 90 million people in Africa (Macdonald *et al*., 2009).

[This section will be fed by an assessment of trends, detections and attributions of climatic changes on water management.]

## 3.3. Drivers of Change for Freshwater Resources, Hazards, and Their Management

### *3.3.1. Climatic Drivers (Precipitation, Temperature, Humidity, Radiation, Seasonal Snow Cover…)*

#### *3.3.1.1. Physical Basis*

We consider the climatic drivers of the freshwater balance (Box 3.1) to be precipitation and evaporation. Because evaporation varies with the wetness and roughness of the surface, it is sometimes more helpful to think of the climatic driver as "evaporative demand", which is the ability of the atmosphere to draw water from a fully wet surface. Although the atmosphere is a small store of water compared to other stores, its water-vapor content is also a climatic driver for present purposes. It is represented as the amount of "precipitable water" in a column through the atmosphere (equal on average to a few tens of millimeters), or as the average specific humidity of the column in grams of vapor per kilogram of (moist) air.

The atmospheric storage capacity depends strongly on the temperature. The hydrological significance of changes in air temperature derives from the Clausius-Clapeyron description of the dependence of saturation specific humidity on temperature: warmer air can hold much more precipitable water as water vapor. Furthermore, it is observed that temperature has increased in recent decades while surface and tropospheric relative humidity (the ratio of specific humidity to saturation specific humidity) have changed little (Hartmann *et al*., 2013). Equivalently, the precipitable water has increased on average. This need not entail a permanent increase in either precipitation or evaporation, and certainly does not rule out regional and interannual to decadal variability.

_____ START BOX 3-1 HERE _____

**Box 3-1. Title?**

The freshwater balance is a relationship that describes all transfers of fresh water across the boundary of a defined volume containing part of the Earth's land surface (Figure 3-2). The sum of these transfers over a given span of time is equal to the change of water storage within the volume, expressed as either a total or a rate. In the analysis of the surface water balance, the study volume excludes aquifers, and when there are no substantial lakes, wetlands or glaciers the annual change of storage in the soil and the vegetation canopy is often assumed to be zero. In this case the surface water balance is simply the sum of precipitation, evaporation and runoff, although changing soil moisture may be of concern over longer periods. In the context of water resources, however, changes of storage in aquifers, lakes and wetlands, glaciers and seasonal snow packs can also be of prime importance.

[INSERT FIGURE 3-2 HERE
Figure 3-2: Components of the freshwater balance of a vertical column extending through the land-surface hydrological system. Pale blue: the atmosphere. Light blue: the land surface (soil; snow; watercourses, wetlands and lakes). Medium blue: aquifers and glacier ice.]

[INSERT FIGURE 3-3 HERE
Figure 3-3: Placeholder (Fig. 1 from WG1 CH12 ZOD, FAQ 12.2); Ch3 Author Team will develop a schematic of the water balance tailored to the needs of the chapter.]

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### *3.3.1.2. Uncertainty*

The leading contributors to uncertainty about the evolution of the climatic drivers are 1) internal variability of the atmospheric system; 2) inaccurate modelling of the atmospheric response to external forcing (for example increased concentrations of greenhouse gases, solar and volcanic influences, and changes of land use), for reasons that range from lack of physical understanding to inadequate knowledge of initial and especially boundary conditions; and 3) uncertainty about the external forcing, as expressed by the range of outcomes from the scenarios chosen for modelling. As shown by Hawkins and Sutton (2011) and Kirtman *et al*. (2013; their figure 11.4 [Figure 3-4]), internal variability and model variability contribute roughly equally to uncertainty near the beginning of CMIP3 projections of temperature and precipitation over the 21st century. Internal variability is of rapidly diminishing significance as the chosen scenarios diverge and they contribute more to total uncertainty. By mid-century, uncertainty in temperature is dominated by the divergence of the scenarios, but variation between models accounts for three quarters of the uncertainty in precipitation after about 2020. This contrast, some implications of which are illustrated by Gosling *et al*. (2011), reflects both the greater complexity of the water cycle and the greater difficulty of simulating it adequately.

[INSERT FIGURE 3-4 HERE
Figure 3-4 [ar5.wg1.ch11.Figure 11.4: included as a placeholder]: The relative importance of each source of uncertainty for decadal mean anomalies (relative to 1986–2005 average) for various quantities is shown through the fractional uncertainty (the 90% confidence level divided by the total uncertainty) based on CMIP3 models. The sources of uncertainty considered are: model uncertainty (blue), scenario uncertainty (green, an estimate of total forcing uncertainty), internal climate variability (orange) and weather noise (yellow in panel "e").]

### *3.3.1.3. Projections*

Some findings in the projections of the climatic drivers on the freshwater in the 21st century are robust in the sense that they emerge from most or all analyses of most scenarios and are consistent with accepted understanding of the operation of the water cycle. The more robust features of CMIP3 simulations of the water cycle during the 21st century, with constraints from 20th-century observations, can be summarized as follows.

- Surface temperature increases more (by about twice as much) over land than over the ocean.
- Warming is greatest over Polar Regions and much greater over the Arctic than the Antarctic. However models underestimate the amplification relative to observations.
- Wet regions become wetter, and dry regions become drier, but the models tend to underestimate observed trends.
- In regions with cold seasons, less of the precipitation falls as snow and the extent and duration of snow cover decrease. In the coldest regions, however, increases in precipitable water due to atmospheric warming mean that increased winter snowfall outweighs increased summer snowmelt.

- Precipitation tends to increase in equatorial, middle and high latitudes and to decrease in subtropical latitudes and global average precipitation increases (Collins *et al*., 2013; their figure 12.13). However, model performance is highly variable, and the variability is greater at regional than global scale.

The less robust but fairly clear projected signals include:
- Rainier rainy seasons and drier dry seasons;
- Consistency between models in projected decreases of precipitation in Mexico and central America, northeast Brazil, southern Africa and the Mediterranean, and projected increases of precipitation in Indonesia and Melanesia;
- Greater evaporative demand, leading to decreases of soil moisture in many regions.

#### *3.3.2.4. Extremes*

It is expected that a warmer climate and a more intense hydrological cycle will be accompanied by more intense extreme events, or equivalently by more frequent events of any given large magnitude. As discussed by Collins *et al*. (2013), one proposed reason for more intense precipitation events is the tendency for the extreme event to "empty" the atmospheric column of its precipitable water, which is projected to increase as described in section 3.3.2.1. Another is a proposed increase in the intensity of convective updrafts, which are usual accompaniments of most heavy thunderstorms.

Kharin *et al*. (2007) found that 24-hour precipitation amounts (annual extremes) which had return periods of 20 years in 1981-2000 had return periods roughly three times shorter in 2081-2100. The return periods were shorter for the more extreme SRES emissions scenarios A1B and A2 than for the more moderate B1 scenario. Agreement between GCM-simulated extremes and extremes observed in reanalysis was good in the extra-tropics but poor in the tropics. In spite of the intrinsic uncertainty of sampling infrequent events, Kharin *et al*. found that variation between GCMs was the dominant contributor to uncertainty, as did Hawkins and Sutton (2011) for decadal mean global precipitation (Figure 3-4).

Min *et al*. (2011) showed that the observed intensification of large-magnitude precipitation events can be attributed reliably to anthropogenic forcing, although there are details that remain obscure. For example the GCMs do not simulate the observed intensification adequately. Pall *et al*. (2011) studied a particular episode of intense hydrological activity, and carried the attributive analysis significantly further than has been seen hitherto. They found that it is *very likely* that global anthropogenic greenhouse gas emissions substantially increased the risk of flooding in England and Wales in autumn 2000.

Nicholls *et al*. (2011) noted that GCM-simulated changes in the incidence of droughts vary widely, so that there is at best *medium confidence* in the projections. Regions where droughts are projected to intensify (that is, become longer and more frequent) include the Mediterranean, central Europe, central North America and southern Africa.

### ***3.3.2. Non-Climatic Drivers***

Given the large uncertainty of climate models in translating emissions scenarios into predictions of precipitation change, a wide range of possible future development of non-climatic drivers is compatible with a wide range of climate change, and in particular precipitation change. This means that certain projected hydrological changes (section 3.4) can occur under a wide range of future economic, social and ecological conditions, and thus may lead to very different impacts and vulnerabilities (section 3.5). This is one reason why the new "representative concentration pathways" RCP (Moss *et al*., 2010), *i.e.*, time series of radiative forcing and emissions, were developed as the basis for climate modeling without first designing and quantifying consistent socio-economic scenarios.

Raskin *et al*. (2010) describe four comprehensive scenarios (Market Forces, Policy Reform, Fortress World and Great Transition) for the 21$^{st}$ century. For 11 world regions, they elaborate not only drivers of the freshwater systems, like population and income changes, inter- and intraregional equity, energy use by fuel, fertilizer use, and land use, but also conditions to assess the vulnerability to water-related climate impacts: amount of people with chronic hunger. In addition, they quantify water-related characteristics like sectional water uses, use-to-resource ratios and water pollution (results at http://www.tellus.org/result_tables/results.cgi). The assumed $CO_2$ emissions of the Policy Reform and Great Transition scenario are below the RCP 2.6, while Fortress World and Market forces are between RCP 8.5 and RCP 6.0 (Raskin *et al.*, 2010). "Carbon dioxide emissions in the Policy Reform and Great Transition scenarios fall below the lowest range of the IPCC scenarios. The RCP 2.6 trajectory, the most ambitious emissions reduction scenario currently being considered by IPCC, relies on massive deployment of carbon sequestration (capture of CO2 from power plant waste streams with subsequent underground storage), though this remains an unproven technology at anything like the scales envisioned. By contrast, deeper and more rapid penetration of renewable energy and efficiency in Policy Reform reduces the need and delays deployment of sequestration technology, while the dematerialized life-styles and moderated population growth in Great Transition reduces its role still further." (Raskin *et al.*, 2010).

["Shared Socio-economic Pathways" SSPs will be included when ready. It will be associated with the non-climatic changes of water demand.]

## 3.4. Projected Hydrological Changes

### *3.4.1. New Ways/Methodologies Estimating/Preparing Future Changes*

Since the AR4 very many assessments of the potential impact of climate change on hydrological characteristics have been published. The vast majority have applied what has become the standard impact assessment methodology, using information from climate models to perturb an historical baseline weather record and using some form of hydrological model to simulate river flows, recharge or water quality. There have, however, been a number of methodological developments, focusing around the use of large numbers of climate scenarios and the use of information derived from regional climate models, the evaluation of the uncertainty associated with different downscaling methods, and the contribution of hydrological model uncertainty to uncertainty in projected impacts. A small number of studies have presented alternatives to the conventional impact assessment methodology.

Most climate change impact assessments have been based on the use of a small number (five or fewer) of scenarios, usually for practical reasons. An increasing number have used larger ensembles from the AR4 CMIP3 scenario set (Gosling *et al.*, 2010; Bae *et al.*, 2011; Jackson *et al.*, 2011; Arnell, 2011b) or ensembles of regional climate models (Olsson *et al.*, 2011), presenting estimates of impact under 10-25 different climates for a given emissions scenario. Some studies have developed "probability distributions" of future impacts by combining results from multiple climate projections and, sometimes, different emissions scenarios, making different assumptions about the relative weight to give to each scenario (Brekke *et al.*, 2009; Manning *et al.*, 2009). These studies conclude that the relative weightings given are typically less important in determining the distribution of future impacts than the initial selection of climate models considered.

Hydrological impact assessments have largely used the "delta-method" to create catchment-scale scenarios, applying projected changes in climate either to an observed baseline or with a stochastic weather generator. Some studies have used weather series simulated by a regional climate model directly to drive a catchment model, after applying some form of bias correction (van Pelt *et al.*, 2009). Yang *et al.* (2010), for example, describe a distribution-based scaling method which adjusts the regional climate model baseline weather to match the variability in the observed baseline and applies the adjustment to simulated future weather; unlike the delta method, this means that the simulated future weather incorporates changes in year-to-year and day-to-day variability as projected by the regional model.

A wide range of methods has now been developed in the literature for downscaling climate information from the climate model scale to the scales most useful for hydrological impact models (Fowler *et al.*, 2007). Systematic evaluations of different methods have demonstrated that estimated impacts can be very dependent on the approach used to downscale climate model data (Chen *et al.*, 2011; Segui *et al.*, 2010), and the range in projected change between downscaling approaches can be as large as the range between different climate models. Fowler *et al*. (2007) suggested that the effect of different downscaling methodologies should be incorporated within a probabilistic approach using multiple scenarios, but this has not yet been applied in practice (*to confirm*).

Impact assessments typically assume that the hydrological model parameters do not change over time as climate changes. An increasing number of studies have compared the effect of hydrological model parameter uncertainty on projected future hydrological characteristics with the effect of scenario uncertainty (Steele-Dunne *et al*., 2008; Cloke *et al*., 2010; Arnell, 2011a). These show that the effects of parameter uncertainty are small when compared with the range from a large number of climate scenarios, but can be substantial when only a small number of climate scenarios is used. Vaze *et al*. (2010) systematically evaluated the assumption that model parameters are unchanging by comparing model performance in Australia during dry and wet periods; they concluded that the most robust projections of the effect of climate change would be produced using model parameters based on data from dry, rather than wet, periods.

As noted above, the vast majority of published impact assessments have followed the conventional "top-down" scenario-driven approach, albeit with increasing degrees of sophistication and awareness of uncertainties. Other approaches are, however, feasible. Cunderlik and Simonovic (2007) for example developed an inverse technique, which starts by identifying critical hydrological changes, uses a hydrological model to determine the meteorological conditions which trigger those changes, and then interprets climate model output (via a weather generator) to identify the chance of these meteorological conditions occurring in the future; Fujihara *et al*. (2008a; 2008b) applied the technique to estimate changes in flood and drought characteristics in a catchment in Turkey. The primary advantage of this approach appears to be that it is not necessary to use the hydrological model to simulate future hydrological characteristics, but it is not apparent that it leads in principle to different conclusions to the conventional approach. Another alternative approach, which appears to be more widely suitable, was presented by Prudhomme *et al*. (2010). This "scenario-neutral" approach produces a response surface showing the sensitivity of a hydrological indicator to changes in climate, by running a hydrological model with systematically-varying changes in climate. In the example given in Prudhomme *et al*. (2010), climate change is represented by two characteristics of a harmonic function describing the variation in rainfall change through the year and the hydrological indicator is change in the magnitude of the T-year flood (Figure 3-5). Climate scenarios from specific climate models can be plotted on the response surface.

[INSERT FIGURE 3-5 HERE
Figure 3-5: Response surfaces showing change in the 20-year flood for two catchments in the UK, for defined changes in the magnitude of precipitation change and seasonal variability in change (Prudhomme *et al*., 2010). The black dots represent individual climate model scenarios.]

### *3.4.2. Evapotranspiration*

Katul and Novick (2009) emphasize that evapotranspiration (ET) is important in sustaining the global- and continental-scale hydrologic cycle and replenishing the world's freshwater resources. Based on global and regional climate models as well as the physical principles expressed in the Penman–Monteith or Clausius–Clapeyron equations, it is projected that global ET should increase in a warmer climate resulting in an acceleration of the hydrologic cycle. Many uncertainties in both magnitude and direction of long-term trends are apparent. ET is not only primarily affected by rising temperatures but also by decreases in bulk canopy conductance associated with rising $CO_2$ concentrations, or large-scale land cover and land use changes (Katul and Novick, 2009).

Another approach to quantify evapotranspiration under changing climates is presented by Serrat-Capdevila *et al*. (2011). They used field observations, theoretical evaporation models and meteorological predictions from global climate models for a semi-arid watershed in the USA. Results indicate that evapotranspiration rates at the studied field sites will remain largely unchanged due to stomatal regulation. Increases in the length of the growing season and hence increased water use and atmospheric demand, will lead to greater groundwater deficits and decreased streamflow (Serrat-Capdevila *et al*., 2011). The observed and estimated global and regional trends in ET support an ongoing intensification of the hydrologic cycle (Huntington, 2010).

### 3.4.3. Soil Moisture and Permafrost

[projected changes in soil moisture and permafrost will be assessed.]

### 3.4.4. Glaciers

#### 3.4.4.1. Observed and Projected Changes

As documented by Comiso *et al*. (2013), glaciers around the world have continued to lose mass steadily. All projections of glacier mass balance for the 21st century (Church *et al*., 2013) show continued mass loss, at scales ranging from single glaciers (Brown *et al*. 2010) to mountain ranges (Zemp *et al*., 2006) to the globe (Radić and Hock, 2011). The ultimate fate of the bulk of the glacier melt water is to contribute to sea-level rise (Church *et al*., 2013). Here we focus on the hydrological impacts of glacier mass loss.

#### 3.4.4.2. Understanding and Modeling Glacier Hydrology

Progress has been made in the incorporation of glacier sub-models into models of climate and hydrology at basin (e.g., Huss, 2011) and global (e.g., Hirabayashi *et al*., 2010) scales, but much remains to be done. For example the Hirabayashi model reproduces global multi-decadal averages of mass balance very well, but its interannual variability tends to be less than observed and the departures from observations are large in some glacierized regions. Like other models, it is a temperature-index model in which surface ablation (melting and sublimation) is linearly proportional to the sum of positive degree-days. Temperature-index models perform accurately when calibrated against observations, and are indispensable tools for water-resources management in data-poor settings and for making projections. However, they simplify all the details of the energy balance that are responsible for the ablation, and these details can vary greatly from basin to basin. Incorporating glacier-specific energy-balance schemes into climate models, so that it is not necessary to do off-line hydrological calculations based on model temperature outputs, is a task for the future. It will be challenging not least because the glaciers usually occupy only a small fraction of the surface of the GCM grid cell, and their topography and elevation ranges differ greatly from those of the model.

#### 3.4.4.3. Hydrological Impacts of Glacier Mass Loss

The seasonal distribution of melt water runoff in glacierized catchments differs from that in snow-covered catchments, reaching a maximum in summer rather than spring. As the glaciers shrink in a warming climate, their relative contribution to basin runoff decreases and the annual runoff peak shifts from summer to spring. This shift is one of the most reliably expected hydrological impacts of a warmer climate. It has been simulated by Hagg *et al.* (2007, 2010) among many others. Huss (2011) showed that, even in large European basins with minor glacier cover in their alpine headwater catchments, the relative importance of high-summer glacier melt water can be substantial and the consequences of projected glacier shrinkage can be serious.

The other leading glacier-hydrological response to warming is an expected peak in the total annual production of melt water. As melt water production $B(t)$ per unit area increases, in agreement with understanding of the energy balance, and total glacierized area $S(t)$ decreases, in agreement with observations of past glacier behavior, $B(t) \times S(t)$ passes through a maximum. This total melt water peak has of course already been passed in basins that have lost all of their glaciers since the maximum extent attained during the Little Ice Age, but in most basins that retain glaciers today the maximum lies in the future. Xie *et al*. (2006) assumed warming rates of 0.02 and 0.03 K $a^{-1}$ and projected peak-meltwater dates between 2010 and 2050 in different regions of China. Huss (2011) projected a peak between the present and 2040 for the European Alps. Radić and Hock (2011) projected a broad global maximum between

2060 and 2080. There is *medium confidence* [TO BE CONFIRMED] that the date of the peak will fall in the present century in most inhabited glacierized regions.

If they are in long-term equilibrium, glaciers reduce the interannual variability of catchment water resources by storing water during cold or wet years and releasing it during warm years (Viviroli *et al*., 2011). As the glaciers shrink, the water supply therefore becomes less dependable.

### *3.4.5. Runoff and Stream Flow*

Since the publication of the AR4 a very large number of assessments of the impact of climate change on runoff and streamflow have been published, representing most parts of the world; the spatial gaps identified in AR4 have been plugged to a very large extent. However, studies in different catchments have used different models, different climate scenarios (although increasingly based on the AR4 CMIP3 climate model set) and different ways of constructing scenarios from climate models. This makes it difficult to compare studies in different places.

A number of global-scale assessments have used global hydrological models with climate scenarios to produce broad assessments of changes in runoff and streamflow (e.g. Gosling *et al*., 2010; Fung *et al*., 2011; Doll and Zhang, 2010), and one assessment used directly the output from a high-resolution global climate model (Hirabayashi *et al*., 2008). The projected changes (Figure 3-6) are dependent on the climate scenarios used, but it is possible to identify a number of consistent patterns. Average annual runoff is generally projected to increase at high latitudes and in the wet tropics. Runoff is projected to decrease in most dry tropical regions. However, there are some regions where there is very considerable uncertainty in the magnitude and direction of change, specifically south Asia and large parts of South America. Both the patterns of change and the uncertainty is largely driven by projected changes in precipitation, with uncertainty in projected changes in rainfall across South Asia being particularly significant.

[INSERT FIGURE 3-6 HERE
Figure 3-6: Map of change in average annual runoff across the global domain (to follow)]

Figure 3-7 shows change in mean monthly runoff for nine catchments across the globe, under the same seven climate model patterns scaled to represent an increase in global mean temperature of 2ºC above the 1961-1990 mean (Hughes *et al*., 2011; Kingston & Taylor, 2010; Nobrega et al., 2011; Xu *et al*., 2011; Arnell, 2011b). In each case, there is considerable uncertainty in the percentage change in mean monthly runoff between the scenarios, and in most – but not all – catchments runoff may either increase or decrease.

[INSERT FIGURE 3-7 HERE
Figure 3-7: Change in mean monthly runoff in 9 catchments, with a 2ºC increase in global mean temperature (above 1961-1990) and seven climate models (to be redrawn): (Hughes *et al*., 2011; Kingston & Taylor, 2010; Nobrega et al., 2011; Xu *et al*., 2011; Arnell, 2011b)]

There is a much more consistent pattern of future change in the timing of streamflows in areas with regimes currently influenced by snowfall and snowmelt. A global analysis (Adam *et al*., 2009) with multiple climate scenarios shows a consistent shift to earlier peak flows, except in some high-latitudes areas where increases in precipitation are sufficient to result in increased, rather than decreased accumulation. The greatest changes are found near the boundaries of regions which currently experience considerable snowfall, where the marginal effect of higher temperatures is greatest.

### *3.4.6. Groundwater*

Since AR4, research on the impact of climate change on groundwater has been strongly intensified (approx. 70 papers identified for the period 2007-2010). Many studies focused on changes in groundwater recharge, while some, for smaller aquifers, also considered groundwater hydraulics. Often, an ensemble of climate scenarios was applied to better understand the uncertainty of projected groundwater recharges. Besides, coupled models, e.g. of the vegetation-soil-groundwater system, were applied.

Future groundwater recharge is expected to be influenced by changes in precipitation intensity. However, it is not clear under what circumstances increased precipitation intensity will tend to decrease groundwater recharge, due to exceedance of infiltration capacity, or to increase it, due to a fast percolation through the root zone from where water otherwise would be evapotranspired (Kundzewicz and Döll, 2009; Owor *et al.*, 2009). Projected groundwater recharge, like other hydrological variables, is subject to large uncertainty due to different climate models being used to translate emissions scenarios into climate input for hydrological models (Hendricks Franssen, 2009). In addition GCM climate scenarios always need to be downscaled before they can be used as input of hydrological models. The uncertainty of the climate change impact on groundwater recharge that arises from the choice of downscaling method can be greater, for a given GCM scenario, than the uncertainty due to the emissions scenario (Holman *et al.*, 2009).

Fifteen climate models resulted in either increases or decreases of groundwater recharge in the semi-arid Murray-Darling Basin in Australia, looking at 2030 as compared to 1990 (Crosbie *et al.*, 2010). Five climate models that project changes in precipitation by -25% to +20% (2080-99 as compared to 1980-99, emissions scenario A1B) for a study site in the semi-arid part of the USA result in a change of groundwater recharge by −75% to +35% (Ng *et al.*, 2010). Four climate models (emissions scenario A2, 2070-99 as compared to 1961-2000) lead to estimates of groundwater recharge changes in a very humid aquifer at the Pacific coast of the USA and Canada between −1.5% and +25% (Allen *et al.*, 2010). Six different regional climate models that provide input to a physically-based surface-subsurface flow model of an aquifer in Belgium lead to projected groundwater table declines of up to 8 m by the 2080s (emissions scenario A2) (Goderniaux *et al.*, 2009). Averaged over the whole German Danube basin, slight precipitation decreases are projected to lead to a decrease of groundwater recharge by more than 10% between 2010 and 2060, and to a decline of the groundwater table elevation by 10±3 m (mean behaviour of an ensemble of 12 climate scenarios, and min/max values) (Barthel *et al.*, 2010). In a scenario of an environmentally-oriented society, the decreased resource availability can be balanced almost completely by decreased industrial and domestic water demand (Barthel *et al.*, 2010); however, the possible climate-induced extension of irrigation was not considered.

The impact of climate change on groundwater also depends, in a site-specific manner, on soil and subsurface material (van Roosmalen *et al.*, 2007), and on vegetation, in particular on the climate-induced changes of vegetation. Deeper roots and increased vegetation cover generally decrease total runoff but also tend to increase the fraction of the total runoff that becomes groundwater recharge. In a warmer climate, leaf area is modelled to decrease in Australia and thus groundwater recharge to increase (taking into account stomatal closure due to increased atmospheric CO2), such that even with slightly decreased precipitation and an increased temperature, groundwater recharge may still increase (Crosbie *et al.*, 2010; McCallum *et al.*, 2010). Depending on the type of grass in Australia, the same change in climate may either lead to an increase or a decrease of groundwater recharge (Green *et al.*, 2007). For a location in the Netherlands a biomass decrease was computed for any of eight climate scenarios (emissions scenario A2).using fully coupled vegetation and variably saturated hydrological model. The resulting increasing groundwater recharge up-slope was simulated to lead to higher water tables and an extended habitat for down-slope wet-adapted vegetation (Brolsma *et al.*, 2010).

Sea level rise during the 21st century is likely to leave many flat coral islands without a reliable groundwater source but in coastal areas with a land surface elevation of a few meters or more, groundwater resources will be is more strongly impacted by changes in groundwater recharge than by sea-level rise (Kundzewicz and Döll, 2009). In the permeable Israeli coastal aquifer, 1 m of sea level rise in 100 years would be slow enough for groundwater equilibrium conditions to prevail, and the fresh-saline water interface would be shifted by the same amount as the shoreline, e.g. 400 m in case of a slope of 0.25%; halving the groundwater recharge of 200 mm/yr would shift the interface by another 800 m (Yechieli *et al.*, 2010). Impact of sea level rise on groundwater in the low-lying Dutch Delta region is restricted to areas within 10 km of the coastline and main rivers, and the groundwater table at 5 km distance from the coastline and main rivers will increase by 40% of sea-level rise by the year 2100 (Oude Essink, G. H. P. *et al.*, 2010). Land subsidence further inland due to continued land drainage, with peat oxidation and clay shrinkage, will cause decreasing groundwater levels further inland. There, stronger upward seepage of saline deep groundwater will increase salinization of the shallow groundwater and the surface waters (Oude Essink, G. H. P. *et* *al*., 2010). In a shallow aquifer at the Mediterranean coast of Morocco, the main impact of climate change will be a decrease of renewable groundwater resources due a decline of groundwater recharge. Groundwater salinity will increase sharply but only within the first kilometre of the current coastline. Further inland, groundwater salinity might increase due to reduced aquifer flow velocities (Carneiro *et al*., 2010).

Permafrost degradation is one of the main causes responsible for a dropping groundwater table at the source areas of the Yangtze River and Yellow River, which in turn results in lowering lake water levels, drying swamps and shrinking grasslands (Cheng and Wu, 2007). Decreasing snowfall may lead to lower groundwater recharge even if precipitation remains constant; at sites in the southwestern USA, snowmelt provides at least 40-70% of groundwater recharge, although only 25-50% of average annual precipitation falls as snow (Earman *et al*., 2006). An indirect impact of climate change on groundwater recharge can occur in irrigated areas with increased water requirements due to increased potential evapotranspiration and growing periods; there, groundwater recharge may increase due to increased return flows of irrigation water (Toews and Allen, 2009).

Changes in groundwater recharge also effect streamflow in rivers. In a catchment of the Upper Nile basin in Uganda, increased potential evapotranspiration as occurring under at high global temperature increases is projected to decrease groundwater outflow to the river so much that the spring discharge peak disappears and the river flow regime changes from bimodal to unimodal (one seasonal peak only) (Kingston and Taylor, 2010). If the groundwater table is close to the land surface (less than approx. 2 m) and the soil is relatively dry, groundwater has a discernible impact on land surface fluxes (Ferguson and Maxwell, 2010). Thus, there is a feedback between groundwater and precipitation (Jiang *et al*., 2009) but it is not well established to what extent regional climate response to anthropogenic climate change depends on groundwater-land surface feedbacks (Ferguson and Maxwell, 2010).

### *3.4.7. Water Quality*

Watershed and lake projections, using different scenarios and models, show an increase in eutrophication, notably in lakes, as a result of temperature increases. They also show a reduction in mixing patterns and higher N and P loads, with unpredictable N:P ratios. Eutrophication results in oxygen depletion, eventual solubilization of phosphorus and heavy metals from sediments, and the formation of algal blooms producing cyanotoxins (Marshall and Randhir 2008; Loos *et al*., 2009; Bonte & Zwolsman 2010; Sahoo *et al*., 2010; Trolle *et al*., 2011). Simulations also suggest that in order to control eutrophication, nutrient loads should be reduced to a greater extent than would be required under scenarios which ignore climate change (Trolle *et al*., 2011; Marshall and Randhir, 2008).

The higher flows expected during part of the winter and/or early spring would tend to increase the loads of sediments, nutrients and organic matter, while warmer temperatures would reduce the dissolved oxygen content (Brikowski, 2008; Marshall and Randhir, 2008; Ducharne 2008).

Although arid and semiarid regions, inhabited by about one fifth of the world's population, rely on groundwater, little research has been performed to assess the future impacts of climate change on the water quality of aquifers (IAH, 2011).The transport of pathogens in karstic or shallow aquifers resulting in higher concentrations during extreme rain events and a reduction in pathogen content during hot and dry summers (Butscherand Huggenberger, 2009; Rozemeijer *et al*., 2009).

From the different reported projections it is evident that results are highly dependent on (Sahoo *et al*., 2010; Trolle *et al*. 2011 Bonte and Zwolsman, 2010; Kundzewicz and Krysanova 2010): (a) local conditions; (b) the climatic and environmental assumptions made; and (c) the current impacts, most of which are dynamic and anthropogenic in origin.

Based on literature reviews, it can be concluded there is a need to further control non-point and point sources of pollution to maintain the quality of water under future climate change scenarios. This is necessary to avoid a further reduction in the availability of water due to impairment of its quality (Marshall and Randhir 2008; Butscher and Huggenberger, 2009). According to Trolle *et al*. (2011), traditional scientific tools, such as the critical loading model, will no longer be valid for the management of lakes if air temperatures increase considerably, as they are based mainly on data from temperate regions of the Northern Hemisphere. Similarly, many lake restoration techniques (e.g., alum dosing, oxygenation and bio manipulation) in use today will become less effective.

### *3.4.8. Sediment Load, Soil Erosion (including Land Slide)*

Changes on sediment load and soil erosion depends on climate variables and on expected land use changes. Several studies have modelled potential soil erosion rates assuming unchanged land use conditions, and changes on rainfall factors (R in USLE equation) derived from GCMs scenarios. This R factor depends on storm frequency or storm intensity. In range lands of the USA, Phillips *et al*., (1993) concluded that changes in R translated to changes in the sheet and rill erosion national average of +2 to +16% in croplands, -2 to +10% in pasturelands and -5 to +22% in rangelands under the eight scenarios. Other studies conclude that change in land use (which may be driven by climate change, as well as economics etc.) will be the most important factor in determining soil erosion under future climates. In temperate climates, small adaptations on soil protection practices may provide sustainable soil/land management systems under future climatic conditions, although uncertainties are high in the case of increased frequency and intensity of heavy rainstorms that may affect adversely sediment production (Klik and Eitzinger (2010)

### *3.4.9. Extreme Hydrological Events (Floods and Droughts)*

[This section is currently from the draft of SREX.]

Floods include river floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods, and glacial lake outburst floods. A change in the climate physically changes many of the factors affecting floods (*e.g*., precipitation, snow cover, soil moisture content, sea level, glacial lake conditions) and thus may consequently change the characteristics of floods.

Recently, a few studies for Europe (Lehner *et al*., 2006; Dankers and Feyen, 2008, 2009) and a study for the globe (Hirabayashi *et al*., 2008) have indicated changes in the frequency and/or magnitude of floods in the 21st century at a large scale. Most notable changes are projected to occur in northern and northeastern Europe in the late 21st century, but the results vary between studies. Three studies (Dankers and Feyen, 2008; Hirabayashi *et al*., 2008; Dankers and Feyen, 2009) show a decrease in the probability of extreme floods, that generally corresponds to lower flood peaks, in northern and northeastern Europe because of a shorter snow season, while one study (Lehner *et al*., 2006) shows an increase in floods in the same region. For other parts of the world, Hirabayashi *et al*. (2008) show an increase in the risk of floods in most humid Asian monsoon regions, tropical Africa and tropical South America.

Several studies have been undertaken for UK catchments (Cameron, 2006; Kay *et al*., 2009; Prudhomme and Davies, 2009) and catchments in continental Europe and North America (Graham *et al*., 2007; Thodsen, 2007; Leander *et al*., 2008; Raff *et al*., 2009; van Pelt *et al*., 2009). However, projections for catchments in other regions such as Asia (Asokan and Dutta, 2008; Dairaku *et al*., 2008), the Middle East (Fujihara *et al*., 2008), South America (Nakaegawa and Vergara, 2010), and Africa are rare. Flood probability is generally projected to increase in rain dominated catchments, but uncertainty is still large in the changes in the magnitude and frequency of floods (Cameron, 2006; Kay *et al*., 2009).

There is low confidence (limited evidence and low agreement) in the projected magnitude of the earlier peak flows in snowmelt- and glacier-fed rivers.

Increased evapotranspiration induced by e.g. enhanced temperature or radiation (e.g., Dai *et al*., 2004; Easterling *et al*., 2007; Corti *et al*., 2009), as well as preconditioning (pre-event soil moisture, lake, snow and/or groundwater storage) can contribute to the emergence of agricultural (soil moisture) and hydrological drought.

On the global scale, Burke and Brown (2008) provided an analysis of projected changes in drought based on four indices (SPI, PDSI, PPEA and simulated soil moisture anomaly), and their analysis revealed that SPI, based solely on precipitation, showed little change in the proportion of the land surface in drought, and that all the other indices, which include a measure of the atmospheric demand for moisture, showed a statistically significant increase with an additional 5%–45% of the land surface in drought. This is also consistent with the more recent analysis from Orlowsky and Seneviratne (2011) for projections of changes in two drought indices (CDD and simulated soil moisture) on the annual and seasonal time scales based on a larger ensemble of 23 GCM simulations from the CMIP3. It can be seen that the two indices partly agree on some areas of increased drought (e.g. on the annual time scale, in the Mediterranean, Central Europe, Central North America, Southern Mexico, and South Africa). But some regions where the models show consistent increases in CDD (e.g. Australia, Northern Brazil) do not show consistent decreases in soil moisture. Conversely, regions displaying a consistent decrease of CDD (e.g. in Northeastern Asia) do not show a consistent increase in soil moisture. The large uncertainty of drought projections is particularly clear from the soil moisture projections, with e.g. no agreement among the models regarding the sign of changes in DJF in most of the globe. These results regarding changes in CDD and soil moisture are consistent with other published studies (Wang, 2005; Tebaldi *et al*., 2006; Burke and Brown, 2008; Sheffield and Wood, 2008; Sillmann and Roeckner, 2008) and the areas that display consistent increasing drought tendencies for both indices have also been reported to display such tendencies for additional indices (e.g. Burke and Brown, 2008; Dai, 2011). Sheffield and Wood (2008, their Figure 10) examined projections in drought frequency (for droughts of duration of 4-6 month and longer than 12 months, estimated from soil moisture anomalies) based on simulations with 8 GCMs and the SRES scenarios A2, A1B, and B1. They concluded that drought was projected to increase in several regions under these three scenarios, although the projections of drought intensification were stronger for the more extreme emissions scenarios (A2 and A1B) than for the more moderate scenario (B1). Regions showing statistically significant increases in drought frequency were found to be broadly similar for all three scenarios, despite the more moderate signal in the B1 scenario (their Figures 8 and 9). This study also highlighted the large uncertainty of scenarios for drought projections, as scenarios were found to span a large range of changes in drought frequency in most regions, from close to no change to two- to three-fold increases (their Figure 10).

Regional climate simulations over Europe also highlight the Mediterranean region as being affected by more severe droughts, consistent with available global projections (Giorgi, 2006; Beniston *et al*., 2007; Mariotti *et al*., 2008; Planton *et al*., 2008). Mediterranean (summer) droughts are projected to start earlier in the year and last longer. Also, increased variability during the dry and warm season is projected (Giorgi, 2006). One GCM-based study projected one to three weeks of additional dry days for the Mediterranean by the end of the century (Giannakopoulos *et al*., 2009). For North America, intense and heavy episodic rainfall events with high runoff amounts are interspersed with longer relatively dry periods with increased evapotranspiration, particularly in the subtropics. There is a consensus of most climate-model projections of a reduction of cool season precipitation across the U.S. southwest and northwest Mexico (Christensen *et al*., 2007), with more frequent multi-year drought in the American southwest (Seager *et al*., 2007). Reduced cool season precipitation promotes drier summer conditions by reducing the amount of soil water available for evapotranspiration in summer. For Australia, Alexander and Arblaster (2009) project increases in consecutive dry days, although consensus between models is only found in the interior of the continent. African studies indicate the possibility of relatively small scale (500km) heterogeneity of changes in precipitation 1 and drought, based on climate model simulations (Funk *et al*., 2008; Shongwe *et al*., 2009).

Global and regional studies of hydrological drought (Hirabayashi *et al*., 2008; Feyen and Dankers, 2009) project a higher likelihood of streamflow drought by the end of this century, with a substantial increase in the number of drought days (defined as streamflow below a specific threshold) during the last 30 years of the 21st century over North and South America, central and southern Africa, the Middle East, southern Asia from Indochina to southern China, and central and western Australia. Some regions, including Eastern Europe to central Eurasia, inland China, and northern North America, project increases in drought. In contrast, wide areas over eastern Russia project a decrease in drought days. At least in Europe, streamflow drought is primarily projected to occur in the frost-free season.

## 3.5. Impacts, Vulnerabilities, and Risks – for Human and Environmental Systems

### *3.5.1. Availability of Water Resources (including Conflicts among Sectors and Allocation Issues)*

It is predicted that a reduction in local water sources will lead to increased demand on regional water supplies. Changes in precipitation patterns may lead to reductions in river flows and falling groundwater tables, and cause saline intrusion in rivers and groundwater in coastal areas. Detected declines in glacier volumes due to increased melting and reduction in the precipitation of snow will reduce river flows at key times of the year, causing substantial impacts on water flows to mountain cities (Satterthwaite, *et al*. 2007).

Water resources are distributed unevenly around the world, and so too are human and environmental demands and pressures on the resource. One assessment suggests that around 80% of the world's population is currently exposed to high levels of threat to water security, as characterized a range of indicators including not only the availability of water but also demand for water and pollution (Vorosmarty *et al*., 2010). The greatest threats are across much of Europe, in south Asia, eastern and northeastern China, and parts of southern Africa and the eastern United States. Climate change has the potential to alter the availability of water and therefore threats to water security.

Global-scale analyses so far have concentrated on measures of resource availability rather than the multi-dimensional indices used in Vorosmarty *et al*. (2010). All have simulated future river flows or groundwater recharge using global-scale hydrological models. Some have assessed future availability based on runoff per capita (Arnell *et al*., 2011; Fung *et al*., 2011), whilst others have projected future human withdrawals and characterized availability by the ratio of withdrawals to runoff or recharge availability (Arnell *et al*., 2011). [*there will be more*]. Döll (2009) constructed a groundwater sensitivity index which combined water availability with dependence on groundwater and the Human Development Index. There are several key conclusions from this set of studies. First, the spatial distribution of the impacts of climate change on resource availability varies considerably with the climate model used to construct the climate change scenario, and particularly with the pattern of projected rainfall change (Döll, 2009; Arnell *et al*., 2011). There is a strong degree of consistency in projections of reduced availability around the Mediterranean and parts of southern Africa, but much greater variation in projected availability in South and East Asia. Second, over the next few decades and for increases in global mean temperature of less than around 2ºC above pre-industrial, future changes in population will largely have a greater effect on future resource availability than climate change (Fung *et al*., 2011), although climate change will regionally exacerbate or offset population pressures. With increases in global mean temperature of above 2ºC, however, the climate change effect dominates changes in future resource availability (Fung *et al*., 2011) [*this conclusion needs support from other studies*]. Third, climate policy only avoids a small proportion of the impacts of climate change on water resources. Depending on indicator, a climate policy which achieves a 2ºC target avoids between 5 and 21% of the impacts on exposure to increased water stress in 2050 of a "business-as-usual" policy which reaches 4ºC, and avoids between 15 and 47% by 2100 (Arnell *et al*., 2011).

[perhaps tabulate some results – but there are differences in indices between studies which make comparisons difficult].

#### *3.5.1.1. Groundwater*

Under climate change, reliable surface water supply is likely to decrease due to increased temporal variations of river flow that are caused by increased precipitation variability and decreased snow/ice storage. Under these circumstances, it might be beneficial to take advantage of the storage capacity of groundwater and increase groundwater withdrawals. However, this option is only sustainable where groundwater withdrawals remain well below groundwater recharge. Groundwater is not likely to ease freshwater stress in those areas where climate change is projected to decrease groundwater recharge and thus renewable groundwater resources (Kundzewicz and Döll, 2009). In the A2 (B2) emissions scenario, by the 2050s, 18.4-19.3% (16.1-18.1%) of the global population of 10.7 (9.1) billion would be affected by decreases of renewable groundwater resources of at least 10% (Döll, 2009). The highest vulnerabilities, which are quantified by multiplying percent decrease of groundwater recharge with a sensitivity index reflecting water scarcity, dependence of water supply on groundwater and the human development, are found at the North African rim of the Mediterranean Sea, in southwestern Africa, in northeastern Brazil and in the central Andes, which are areas of moderate to high sensitivity (Figure 3-8). For most of the areas with high population density and high sensitivity, model results indicate that groundwater recharge is unlikely to decrease by more than 10% until the 2050s (Döll, 2009).

[INSERT FIGURE 3-8 HERE
Figure 3-8: Human vulnerability to climate change induced decreases of renewable groundwater resources by the 2050s for four climate change scenarios. The higher the vulnerability index (computed by multiplying percent decrease of groundwater recharge by a sensitivity index), the higher is the vulnerability. The index is only defined for areas where groundwater recharge is projected to decrease by at least 10%, as compared to the climate normal 1961-90 (Döll, 2009).]

### *3.5.2. Water for Agriculture (Small to Large Scales)*

Higher temperatures and increased variability of precipitation would, in general, lead to increased irrigation water demand, even if the total precipitation during the growing season remains the same (Bates *et al*., 2008). Irrigation is vulnerable to climate change since it depends on the availability of water from surface and ground water sources which are a function of precipitation. Climate change has a potential to impact rainfall, temperature and air humidity, which have relation to plant evapotranspiration and crop water requirement. Since irrigation is also a common semi-arid activity, increase in temperature may create high crop water demand. This affects crop productivity in both small and large scale irrigations systems.

### *3.5.3. Hydropower Generation*

A few studies have applied a larger number of climate scenario to assess the impact of climate change on hydropower production for individual dams or small regions (e.g. Markoff and Cullen, 2008; Schaefli *et al*., 2007). Considering 11 GCMs, hydropower production of Lake Nasser (Egypt) was computed to remain constant until the 2050s but to decrease, on average (ensemble mean), to 93% (92%) of its current climate mean annual production for A2 (B1) emissions scenario, following the downward trend of river discharge (Beyene *et al*., 2010).

Hydropower production is affected by changes in the annual average river discharge as well as by seasonal flow shifts and daily flow variability. Uncertainty in future precipitation due to differences in the predictions of individual climate models appears to be more important for the prediction of future hydropower production and revenues than uncertainty in future temperatures in the Pacific Northwest of the USA, and climate model-related uncertainties are larger than differences between emissions scenarios (Markoff and Cullen, 2008). In snow-dominated basins, increased discharge in winter and lower and earlier spring floods are expected. This makes the annual hydrograph more similar to seasonal variations in electricity demand, providing opportunities for operating dams and power stations to the benefit of riverine ecosystems (Renofalt *et al*., 2010, for Sweden). In general, climate change requires adaptation of operating rules (Minville *et al*., 2009; Raje and Mujumdar, 2010) which may, however, be restricted by reservoir storage capacity. In California, for example, high-elevation hydropower systems with small storage, which rely on the storage capacity of the snowpack, are projected to suffer from decreased hydropower generation and revenues due to the increased occurrence of spills, unless precipitation increases significantly (Madani and Lund, 2010). Storage capacity expansion would help increase hydropower generation but might not be cost effective (Madani and Lund, 2010). Economic assessment procedures for hydropower plants considering climate change have been developed (Block and Strzepek, 2010; Jeuland, 2010; Molarius *et al*., 2010).

### *3.5.4. Water Supply and Sanitation*

The impact of climate change on water supply affects different sectors and different users through a complex series of mechanisms. The 9% increase in hospital admissions which has occurred in Philadelphia to treat gastrointestinal diseases in elderly people caused by increases in turbidity in the influent of drinking water plants fully complying with the US standards (Schwartz *et al.*, 2000). As concerns for the deterioration of the quality of water sources grow, one point of vulnerability is the lack of reliable methods to assess the impact of climate change on water quality. This is in part because monitoring protocols are used to follow up the impacts of pollution rather than those of climate (Kundzewicz and Krysanova, 2010; Rode *et al.*, 2010; Emelko *et al.*, 2011).

Food security is a global concern, tightly linked to water and energy supply issues (Jones, 2008). More water is needed to irrigate in order to produce additional food for growing populations, to improve incomes in many countries – particularly in developing countries located partially or entirely in arid and semiarid regions - and even to produce biofuels to mitigate climate change. Irrigation is responsible for 81% of the total use of water in developing countries, contrasting with 45% in developed countries (Green et al., 2010; Jiménez, 2011). For rainfed areas, variability in the flow of streams or the extraction of water from aquifers at greater depths will result in problems for farmers who may be unable to cope with the additional costs required to allow access to water. In areas where competition for water among users is considerable, agriculture will probably be the sector to suffer the most (Jones, 2008). Increasing industrialization will result in increased demand for water for industrial processes and energy production, and water will become a critical aspect in both. Up to 70% of the water for cooling at power plants is supplied from fresh water resources. Extended droughts are increasingly jeopardizing the reliability of nuclear power plants. For instance, in France in 2003, heat waves caused shutdowns or reduction of output in 17 plants, forcing the nation to import electricity at more than 10 times the normal cost (Ackerman and Stanton, 2008). To properly select a technology, novel methodologies to compare them based on their water and carbon footprint and other environmental costs have been proposed (Duvivier and Laborelec, 2008; Pistochini and Modera, 2010). With typical plant efficiencies of about 40%, the thermal loses in water sources are around 60%. Thermal pollution may be exacerbated because of high temperatures of water and variations in the flows of the receiving water bodies, particularly in tropical areas (Ackerman and Stanton 2008; Pistochini and Modera, 2010). However, it should be noted that cooling systems can be used to recover both water and energy, for instance for greenhouse irrigation, air conditioners, heating and many other applications (Jiménez, 2001).

Ecosystems are important for many reasons, one of which is that they provide services that are necessary for the safe and reliable supply of water (Jiménez 2011). Impacts on ecosystems may result from higher demand for water and also an increase in the proportion extracted from natural systems under low-flow conditions (Butscher and Huggenberger, 2009). Forested watersheds could be more susceptible to pest infestations, diseases and fires under climate change scenarios. This could lead to deforestation with associated impacts on water quality, and flooding (Butscher and Huggenberger, 2009; Zwolsman 2008). Wetlands have proven to be efficient barriers to hurricane impacts for settlements. Peatlands, store nearly 30% of all land-based carbon; this is equivalent to 75% of all atmospheric carbon, and twice the carbon stock in the forest biomass of the world (IAH, 2011). Ecosystems are more prone to suffer from lack of water in developing countries, even in those that are water-rich, such areas of Central America. Here the availability of water is eight times the mean world value. Population growth, economic development and concentrated settlement in limited areas within these countries, combined with lower and more variable precipitation, will lead to a worrying disturbance in the ecological use of water (Jiménez and Navarro, 2010). Climate change has potential impacts on municipal supply because of the introduction of variation in water quantity and quality, resulting in lower reliability of the service. This may be combined with an increase in demand, greater competition among users and effects on the water supply infrastructure as a result of extreme events (Arnell and Delaney 2006; Jiménez, 2011). Options available to meet variable and uncertain scenarios include: (a) the adoption of the "water flex" concept to provide supply from a wide range of water sources, instead of relying on only one or two as is traditionally done; (b) the more intensive use of aquifers to store and depollute water as is achieved with bank filtration systems (c) the augmentation of storage capacity and its management in a flexible way to face droughts; (d) the consideration of economic and social aspects to provide a fair and equitable distribution of water among different stakeholders to reduce vulnerability to climate change; (e) better site selection for water supply infrastructure to avoid flood damage and improved protection of pre-existing facilities; (f) the construction of new plants or the enhancement of existing ones to allow them to cope with variations in the quality of raw water; (g) increased reuse and recycling; (h) the selection of technologies with low energy consumption; (i) adoption of the concept of properly and reintegrate water into the environment instead of partially treating it; and, (j) desalinating water in settlements located near the coast. The specific measures applied will depend on local conditions but in general will fall into three categories associated with different geographical regions at risk: (a) low-lying areas and river deltas; (b) mountainous regions affected by retreating glaciers, snowmelt or droughts; and (c) arid and semiarid areas (Seah, 2008; Jiménez and Asano, 2008; OFWAT, 2009; NACWA, 2009; Jones, 2008; Mukhopadhyay and Dutta, 2010; Sprenger *et al.*, 2011; Emelko, 2011 Jiménez, 2011)

While in developed countries sanitation coverage approaches 99%, in developing ones it is only around 50% and is mostly limited to sewerage transporting untreated wastewater to agricultural fields, rivers, ravines or the sea (Jiménez, 2011). The design of urban drainage systems requires new methods to ensure that the system can continue to function as designed even under future climatic conditions, rather than using procedures based on historical precipitation statistics. Existing sewers and pipelines should be reinforced to reduce infiltration and inflow due to rising sea and groundwater levels. This should be coupled with the proper management of combined sewer overflows (CSOs). Moreover, water from the sewer system may flush back to street level during rainstorms, posing a threat to human health and wellbeing (NACWA, 2009). Worldwide, agriculture and livestock are significant sources of non-point sources of pollution. Other important sources include the disposal of non-treated and treated wastewater, the deposition of atmospheric pollutants, land erosion and leaks from sewers and submerged tanks. As a result of increased precipitation, the pollutants from these sources are expected to increase, further deteriorating the quality of surface and ground water. Those of concern include pathogens and emerging pollutants such as endocrine disrupting compounds (Boxall *et al.*, 2009; Kundzewicz and Krysanova, 2010; Jiménez, 2011; Dipankar *et al.*, 2011; Jiménez and Rose, 2009).

### *3.5.5. Freshwater Ecosystems*

Freshwater ecosystems are the animals, plants and other organisms and their abiotic environment in slow flowing surface waters like lakes, man-made reservoirs or wetlands, in fast flowing surface waters like rivers and creeks, and in the groundwater. They have suffered more strongly from human actions than marine or terrestrial ecosystems. Between 1970 and 2000, populations of freshwater species included in the Living Planet Index declined on average by 50%, compared to 30% for marine and also for terrestrial species (Millenium Ecosystem Assessment, 2005).

Climate change is an additional stressor of freshwater ecosystems. It affects freshwater ecosystems not only by increased water temperatures but also by altered flow regimes, water levels and extent and timing of inundation. In addition, climate change leads to water quality changes (section 3.2.4) including salinization which also influences freshwater ecosystems. Furthermore, freshwater ecosystems are likely to be negatively impacted by human adaptation to climate-change induced flood risk as flood control structures affect the habitat of fish and other organisms (Ficke *et al.*, 2007). In this chapter, we focus on the impacts of altered flow regimes and water quality, while impacts of temperature increases are discussed in chapter 4.

Knowledge about the response of organisms to altered flow regimes is poor, and quantitative relations between flow alteration and biotic changes could not yet been derived (Poff and Zimmerman, 2010). Most species distribution models do not consider the effect of flow regimes, or they use precipitation as proxy for river flow (Heino *et al.*, 2009). Winter peak flow during egg incubation was found to be most decisive for salmon population in the north western USA, together with minimum flow during spawning period (September to November) and stream temperature during the pre-spawning period (August to September) (Battin *et al.*, 2007). Mainly due to strongly increased winter peak flows, salmon abundance was projected to decline by 20-40% by the 2050s (depending on the climate model), the high-elevation areas being affected most. Even a strong restoration effort might not be able to balance these climate change impacts (Battin *et al.*, 2007).

Lake and wetland water levels can be expected to decline due to climate change more often than not, unless increased precipitation balances the increased evapotranspiration due to higher temperatures, with effects on water chemistry and habitat. Larger variability of river flows (including the transformation of intermittent streams to perennial ones and vice versa) that is due to increased climate variability is likely to select for generalist species or those with the ability to rapidly colonize defaunated habitats and possibly lead to a loss of locally adapted species (Ficke *et al.*, 2007). Wetlands in semi-arid or arid environments are hotspots of biological diversity and productivity, and are endangered by extinction in case of decreased runoff generation, resulting in wetland extinction and loss of biodiversity (Zacharias and Zamparas, 2010). Lower river flows might exacerbate the impact of sea level rise and thus salinization on freshwater ecosystems close to the ocean (Ficke *et al.*, 2007). If a tipping point of 5% loss of present day freshwater wetlands will be reached in the Kakadu National Park in North Australia, geese population is projected to decline very rapidly to only a few percent of the current population (Bowman *et al.*, 2010, Traill *et al.*, 2010).

By the 2050s, climate change is projected to impact ecologically relevant river flow characteristics like long-term average discharge, seasonality and statistical high flows more strongly than dam construction and water withdrawals have done up to the year 2000 (Döll and Zhang, 2010). The exception are statistical low flows, with significant decreases both by past water withdrawals and future climate change on one quarter of the land area (Figure 3-9b, Döll and Zhang, 2010). Considering long-term average river discharge, only a few regions, including Spain, Italy, Iraq, Southern India, Western China, the Australian Murray Darling Basin and the High Plains Aquifer in the USA, all of them with extensive irrigation, are expected to be less affected by climate change than by past anthropogenic flow alterations (Figure 3-9a). In the HadCM3 A2 scenario, 15% of the global land area may suffer from a decrease of fish species in the upstream basin of more than 10%, as compared to only 10% of the land area that has already suffered from such decreases due to water withdrawals and dams (Döll and Zhang, 2010). Climate change during the 21st century is expected to increase runoff in northern and central Sweden and make the annual hydrograph more similar to variation in electricity demand, i.e. a lower spring flood and increased run-off during winter months. This could provide opportunities for operating dams and power stations to the benefit of riverine ecosystems (Renofalt *et al.*, 2010).

[INSERT FIGURE 3-9 HERE
Figure 3-9: Comparison of the impact of climate changes to the impact of dams and water withdrawals for long-term average annual discharge (a) and monthly low flow $Q_{90}$ (b). Red colors indicate that the climate change affects the flow variable at least twice as much as dams and water withdrawals do, blue colors the opposite. Positive values indicate the changes due to climate change and withdrawal and dams are either both negative or both positive. Dams and withdrawals in the year 2002, climate change between 1961-1990 and 2041-2070 according to the emissions scenario A2 as implemented by the global climate model HadCM3.]

Also by the 2050s, eco-regions containing over 80% of Africa's freshwater fish species and several outstanding ecological and evolutionary phenomena are likely to experience hydrologic conditions substantially different from the present, with alterations in long-term average annual river discharge or runoff of more than 10% due to climate change and water use (Thieme *et al.*, 2010). One third of fish species and one fifth of the endemic fish species occur in eco-regions that will experience more than 40% change in discharge or runoff (Thieme *et al.*, 2010).

### *3.5.6. Flood*

There is high confidence that absolute socio-economic losses from weather-related disasters are increasing (SREX Report, Chapter 4). There is high agreement, but medium evidence that anthropogenic climate change has so far not lead to increasing losses. This is particularly the case river floods. Exposure of people and economic assets to climatic extremes is almost certainly increasing, and is very likely the major cause of the long-term changes in economic disaster losses (SREX report). Trends in vulnerability vary greatly by location and demography with some areas and groups showing increases and others decreases. There are few studies quantifying non-climate factors such as exposure and vulnerability at global scale, thus the confidence in projections is low.

Most studies of disaster loss records attribute these increases in losses to increasing exposure of people and assets in at-risk areas (Miller *et al.*, 2008), in many cases modulated by societal factors (demographic, economic, political, social) directly related to our vulnerability (Pielke *et al.*, 2005; Bouwer *et al.*, 2007). A few studies claim that an anthropogenic climate change signal can be found in the records of disaster losses (Mills, 2005; Höppe and Grimm, 2009; Malmstadt *et al.*, 2009; Schmidt *et al.*, 2009). There have been several attempts to normalize loss records for changes in exposure and vulnerability, aiming to detect changes on flood hazard rather than the disaster impact. Most of these studies dealing conclude on the absence of climate change induced trends on the normalized losses (Pielke and Downton, 2000; Downton *et al.*, 2005; Barredo, 2009; Hilker *et al.*, 2009), although some studies did find recent increases in losses, related to changes in intense rainfall events (Jiang *et al.*, 2005; Chang *et al.*, 2009). In the case of events related to extreme precipitation (intense rainfall, hail and flash floods), some studies suggest an increase in impacts related to higher frequency of intense rainfall events (Changnon, 2001; Changnon, 2009), although no trends was found for losses from flash floods and landslides in Switzerland (Hilker *et al*. 2009).

The SREX report (2012) conclude that there is no a robust evidence that anthropogenic climate change has led to increasing losses and increasing exposure of people and economic assets is virtually certain to be the major cause of the long-term changes in economic disaster losses. This conclusion is applied to flood risk in developed countries where most data are available using normalize loss data over time considering changes in exposure, but use only partial measures of wealth for vulnerability trends which is questionable. This report noted two main areas of uncertainties. A first related to different approaches to handle variations in the quality and completeness of longitudinal loss data, and their normalization. A second area of uncertainty concerns the impacts of modest weather and climate events on the livelihoods and people of informal settlements and economic sectors, especially in developing countries. These impacts largely excluded from longitudinal impact analysis as there are not systematically reported or documented on national or global databases.

### *3.5.7. Other Sectors*

As seen in the preceding subchapters, most of the sectors are under multiple stresses caused by changes in the hydrological systems. Next to the direct impacts, vulnerabilities, and risks in the water-related sectors, indirect impacts from changes in the hydrological systems are expected in other secondarily-related sectors, such as navigation, transportation, livelihood, tourism etc. (Badjeck *et al*., 2010; Beniston, 2010; Koetse and Rietveld, 2009; Pinter *et al*., 2007; Rabassa, 2009). Further social and political problems can occur, as for example water scarcity and water overexploitation may increase the risks of violent conflicts (Barnett and Adger, 2007).

Due to increases in global temperatures, shifts in tourism and agricultural production and hence passenger and freight transport are expected. A rise in sea levels and increases in frequency and intensity of storm surges, rainstorms and flooding may have consequences for coastal areas (Koetse and Rietveld, 2009). Shifts in precipitation patterns might cause infrastructure disruptions, e.g. with an increasing accident frequency. The costs of inland waterway transport may increase due to increased frequency of low water levels. Most direct impacts and costs are still uncertain and ambiguous (Koetse and Rietveld, 2009). On the other hand extreme high water levels in rivers may lead to increasing sedimentation of navigation channels and hence cause higher costs for navigation for example due to more necessary channel dredging (Pinter *et al*., 2007).

Increased calving from tidewater glaciers implies an increased flux of icebergs, which will increase sailing risks in high-latitude and some mid-latitude waters (Rabassa, 2009). As a consequence of snowline rising and glacier vanishing, damage on environmental, hydrological, geomorphological, heritage, and tourism resources is expected to affect glacierized regions and those communities active in them (Rabassa, 2009). The melting of alpine glaciers and rising snowlines in the European Alps, South American Andes, or Himalayas already affects for example the tourism industry (Beniston, 2011).

## 3.6. Adaptation and Managing Risks

### *3.6.1. Introduction (including IWRM)*

Impacts on the hydrological system and water resources are already resulting from climatic changes and will be more severe in the future. In most countries, adverse effects in water resources are experienced and further expected due to increased frequency and intensity of floods and droughts, intensified erosion and sedimentation, expanding water scarcity, reductions in glaciers, sea ice and snow cover, increased thawing of permafrost, rising sea level, damages to water quality, and pollution of entire ecosystems. Furthermore, climate change impacts on water resources influence directly and indirectly water-depended sectors of the economy and society, such as agriculture, industry and hydropower, supply and sanitation, freshwater ecosystems, and others (Bates *et al*., 2008; Mertz *et al*., 2009; Olhoff and Schaer, 2010; Sadoff and Muller, 2009; UNECE, 2009).

Adaptation to changes in the hydrological system and water resources is of utmost interest to preserve and secure the environment, the economy and in particular the society. With increasing temperatures, predictions of future precipitation suggest regional increases or decreases of water availability by 10% up to 40%. These changes will have major impacts on the water resources which increase the vulnerability of communities, the industry, and many infrastructures. Adaptation measures, which involve a combination of 'hard' infrastructural and 'soft' institutional actions, are needed. Individual regional measures can be identified by 'climate proofing' and implemented as various actions, such as dike construction, governmental programs, and capacity building (Bates *et al*., 2008; Mertz *et al*., 2009; Olhoff and Schaer, 2010; Sadoff and Muller, 2009; UNECE, 2009).

To lessen the aforementioned vulnerability, a crucial role in achieving a sustainable preservation of worldwide water resources lies in their strategic management. Every country and/or region should concentrate on incorporating necessary water-related climate change adaptation schemes into planning, and implementing adaptation measures with applying best practices in water resource management. Successful integrated water management strategies include, among others: capturing society's views, reshaping planning processes, coordinating land and water resources management, recognizing water quantity and quality linkages, conjunctive use of surface water and groundwater, protecting and restoring natural systems, and including consideration of climate change (UN-Water, 2009; Bates *et al*., 2008; Olhoff and Schaer, 2010; Sadoff and Muller, 2009).

A major instrument to explore water-related adaptation measures to climate change is provided with the Integrated Water Resource Management (IWRM), which can be joined with a Strategic Environmental Assessment (SEA). IWRM is an internationally accepted approach for efficient, equitable and sustainable development and management of water resources and water demands, while SEA is an additional planning tool for introducing environmental considerations into IWRM. Multiple guidelines and frameworks dealing with IWRM are published and promoted for implementation by international institutions, such as the UN-Water Status Report on Integrated Water Resource Management and Water Efficiency Plans, the Guidance Notes to Mainstreaming Adaptation to Climate Change by the World Bank, the EU Water Framework Directive, or in reports from UNEP, UNDP or the Global Water Partnership (UN-Water, 2009; European Union, 2000; Bates *et al*., 2008; Olhoff and Schaer, 2010; Sadoff and Muller, 2009).

### *3.6.2. Costs and Benefits of Adaptation*

Some of the major impacts of climate change are likely to be on water resources and subsequently have effects on many human activities. To respond to this challenge, national and international institutions have decided to financially support adaptation projects and as a result there is a need to assess the associated costs. Costs reported in the literature are difficult to compare, notably due to the lack of standardized concepts and methodologies, both in terms of calculations and the reporting of results. This is especially true for the water sector due to differences in the user for water that are considered. The reported global costs for climate change impacts and adaptation vary by two orders of magnitude and mainly focus on the supply of water for municipal, industrial and agricultural purposes (World Bank, 2006; Stern, 2006; Oxfam, 2007; UNDP, 2007; Kirshen, 2007; Fischer *et al*., 2007), and sometimes for ecosystems (UNFCCC, 2007). One study (Parry *et al*., 2009) considers that the 2007 UNFCCC costs of $9–11 billion USD per year for adaptation represent the best estimation for the water supply sector and represent a similar investment to that required to meet the Millennium Development Goal targets for water. In one specific case, Zhu *et al*. (2007) estimated the costs for flood control and residual damage in Sacramento, California. It was shown under climate change scenarios, costs doubled if urbanization was increased. With regard to residual damage, the costs stemming from the lack of water for agricultural irrigation are particularly significant (Medellin-Azuara *et al*., 2008). To maintain water quality standards an additional 6.6-41 million USD per year would be required. For the Huang Ho River in China, Kirshen *et al*. (2007) calculated that to meet the demand for water, annual costs were increased 3.5 fold for one climate change scenario with reference to the baseline. For a second scenario costs could simply not be evaluated as insufficient water was available to meet demand. The estimation of costs also shows that climate change can be beneficial. Under a relatively favorable scenario the costs for effective nutrient management under the Water Framework Directive for the eutrophic Mälar Lake and Stockholm archipelago in Sweden were negligible; however for an unfavorable scenario they increased up to 160 million USD per year (Green, et al., 2010). Preliminary estimations made by Ackerman and Stanton (2008) for the USA reported that hurricane damage could represent a cost of 43 billion USD by 2050, while those for water supply were estimated at 336 billion USD. Of the total estimated cost of hurricane damage, including losses in real estate and effects on the energy and water sectors, the cost of water supply represented nearly half. Another assessment (NACWA, 2009) for the USA, considering effects up to 2050, showed that investments and operating costs for water services could range from 448 to 944 billion USD, with drinking water representing around 70% and sanitation around 30% of the total. Estimations for Central America showed that water tariffs have a significant impact on cost projections. Results were inconclusive when these tariffs did not represent the real cost of water. The cost implications of climate change were higher than the cost of setting up different adaptation measures such as leakage control, reuse and recycling and ensuring the efficient use of water (Jiménez and Navarro, 2010). Other potential costs which were identified in the literature review but not taken into account in the different estimations were: (a) the cost of buying water as happened for the Taihu Lake population in India, where two million people were forced to drink bottled water rather than tap water for a week following impairment of water by an algal bloom episode (Qin *et al.*, 2010) ; (b) the cost of providing hospital assistance to elderly people in Philadelphia because of gastrointestinal diseases linked to the supply of drinking water during periods of high turbidity (Schwartz *et al.*, 2000); and (c) the environmental effects on surface and groundwater as result of extreme weather conditions (Dipankar *et al.*, 2011).

In general, cost estimations fail to represent actual costs for many reasons. These include: (Kirshen, 2007; Ackerman and Stanton, 2008; Parry *et al.*, 2009; EEA, 2007; Jiménez and Navarro, 2010):

- The uncertainty associated with the data used for climatic, social, economic and water quality scenarios, and with the assumptions made in order to obtain results.
- The goals defined for adaptation may vary. They may represent: (i) maintaining a given standard of service, (ii) achieving a new 'optimum' standard of service, or (iii) meeting a new standard of service.
- The limited range of activities considered by the "water sector".
- The consideration of an adaptation based only on public infrastructure using hard technology rather than green solutions
- The lack of estimations of residual damage.
- The use of average climate change scenarios, rather than individual ones.

Another interesting aspect from the literature review was the need to control corruption during the set up and founding of projects to adapt to climate change.

### *3.6.3. Case Studies from Literature*

Papers in the refereed literature on adaptation in the water sector fall into four broad groups. One group comprises analyses of the potential effect of different adaptation measures on the impacts of climate change for specific resource systems (for example Medellin-Azuara *et al.* (2008) in California, Miles *et al.* (2010) in Washington State USA, Pittock and Finlayson (2011) in the Murray-Darling basin in Australia, and Hoekstra and de Kok (2008) on dike heightening in the Netherlands). The second group presents methodologies for assessing the impacts of climate change specifically for adaptation purposes. For example, Brekke *et al.* (2008) and Lopez *et al.* (2009) both propose the use of multiple scenarios for risk assessment.

The third group contains approaches for the incorporation of climate change into water resources management practice. A strong theme to this group of studies is the recommendation that water managers should move from the traditional "predict and provide" approach towards adaptive water management (Pahl-Wostl, 2007; Pahl-Wostl., *et al.*, 2008; Mysiak *et al.*, 2009). Adaptive water management techniques include scenario planning, employing experimental approaches which involve learning from experience, and the development of flexible solutions. These solutions would be unlikely to be entirely technical (or supply-side), and central to the adaptive water management approach is participation and collaboration amongst all stakeholders. However, whilst climate change is frequently cited as a key motivation for the adoption of adaptive water management, there is very little guidance in the literature on precisely how the adaptive water management approach works when addressing climate change over the next few decades. A few examples are given in Ludwig *et al.* (2009). The United Nations World Water Development Report 3, published in 2009 (World Water Assessment Programme, 2009) explicitly advocates adaptive water management as a response to climate change, but emphasizes the development of resilient and noregrets options. These, however, could be interpreted as options that address climate change by aiming for the "worst-case", and the interpretation of adaptive water management in the World Water Development Report is therefore slightly inconsistent with the mainstream interpretation. The US Water Utilities Climate Alliance (WUCA, 2010) provide the most comprehensive overview of ways of delivering adaptive water management which explicitly incorporates climate change and its uncertainty. They proposed a framework with three steps - system vulnerability assessment, utility planning using decision-support planning methods, and decision-making and implementation – and summarized planning methods for decision-supports. These include classic decision analysis, traditional scenario planning and robust decision making (Section 3.6.5).

The fourth group of studies evaluate the practical and institutional barriers to the incorporation of climate change within water management (Goulden *et al*., 2009; Engle and Lemos , 2010; Stuart-Hill and Schultz, 2010; Ziervogel *et al*., 2010; Huntjens *et al*., 2010; Wilby & Vaughan, 2011). The key conclusions from these studies are that institutional structures have the potential to be major barriers to adaptation, that structures which encourage participation and collaboration between stakeholders are likely to be most effective, and that the uncertainty in how climate change may affect the water management system is a significant barrier.

There is, however, a considerably smaller literature describing what water management agencies are actually currently doing to adapt to climate change [*but this will be expanded considerably in the next couple of years*]. There is evidence that a number of agencies are beginning to factor climate change into processes and decisions [*perhaps include a table in the FOD??*] (Kranz *et al*., 2010; Krysanova *et al*., 2010), with the amount of progress strongly influenced by institutional characteristics.

Finish section with examples (there are not many yet) in three areas:

- Attempts to improve adaptive capacity of organizations / institutions
  - Literature on actual or proposed institutional changes
- Examples of actual methodologies for (e.g.) resource assessment
  - Much of this will be in the grey literature
  - UK water supply methodologies (Arnell, 2011b)
  - UK flood frequency calculations
  - US proposed revision to P&G (Brekke *et al*., 2009)
  - EU – Guidance on Water and Adaptation
- Examples of actual "concrete" measures
  - Can we find examples in the literature of actual decisions that have been implemented because (or partly because) of climate change? Not aware of any so far.

### *3.6.4. Limits to Adaptation*

Adaptation to climate change is an economic and social imperative. Adaptation refers to those responses to climate change that may be used to reduce vulnerability or to actions designed to take advantage of new opportunities that may arise as a result of climate (Burton, 2009). The focus of these is on managing risk (IPCC, 2007). Investments in risk based actions are fundamental to reducing the environmental, social and economic cost of climate change. Essential elements for build adaptability are as shown on Table 3-1.

[INSERT TABLE 3-1 HERE
Table 3-1: Access mechanisms to adaptability.]

Adaptation measure to climate changes vary depending on many factors classifications. Factors can be classified either on sectional basis, or on the timing, goal and motive of their implementation. Accordingly, adaptation can include reactive or participatory actions or can be planned or autonomous (UNFCCC, 2007; IPCC, 2007). Planned adaptation is the result of deliberate policy decisions based on the awareness that conditions have change or expected to change. Autonomous adaptation refers to those actions that are taken by individual institutions and communities independently to adjust to their perceptions of climate change risks.

In recent years, literature has emerged that highlight potential limits and barriers to adaptations (Burton, 2009). This literature reflects the reality of our current understanding of adaptation and adaptive capacity. Barriers such as lack of technical capacity, financial resources, awareness, communication etc., are cited in association with adaptation in developing countries.

Water utilities must enhance their capacity to cope with the impacts of climate change and other human pressures in the future by increasing resilience and reliability. To achieve this, they need to better assess their vulnerability, considering not only technical aspects but also social and economic ones, such as (Butscher and Huggenberger, 2009; Zwolsman 2011; Browning-Aiken and Morehouse, 2006): (a) the fact that poor people settle in unsafe areas lacking water services and therefore demand additional public assistance; (b) migration patterns result in demand for services in new areas, sometimes on a temporary basis, resulting in a loss of local knowledge which would aid the selection of low risk areas for settlement; (c) the need to employ better trained staff to deal with problems of water scarcity, which generally only have complex solutions; (d) the need to enforce the law to better use and protect water sources in places where this is not customary; (e) the management of water demand among users in order to satisfy the need for municipal water, including that required for food and energy production. To become "climate proof", water utilities and the water sector in general will need to make additional efforts and incur considerable expense.

### *3.6.5. Dealing with Uncertainty*

One of the key challenges to the incorporation of climate change into water resources management lies in the uncertainty in the projected future changes. A large part of the international literature focuses on this uncertainty, mostly concerned with the development of approaches to quantify uncertainty. Methods have been developed, for example, to use very large numbers of scenarios to produce "likelihood distributions" of indicators of impact (*e.g.*, Lopez *et al.*, 2009), and there is a considerable literature on the effect of different ways of weighting or screening different climate models (Brekke *et al.*, 2008; Chiew *et al.*, 2009). The use of multiple scenarios and the temptation to present impacts in terms of probability distributions, however, begs the question of whether such distributions are meaningful (*need cross reference to WG2 scenarios chapter*). It has been argued (Stainforth *et al.*, 2007; Hall, 2007; Dessai *et al.*, 2009) that the attempt to construct probability distributions of impacts is misguided, largely because of the "deep" uncertainty in possible future climates. Deep uncertainty arises because analysts do not know, or cannot agree upon, how systems may change, how models represent possible changes, or how to value the desirability of different outcomes. Stainforth *et al.* (2007) argue, for example, that all climate models omit some key processes which may influence how climate changes, and the simulations that are available do not therefore necessarily represent the full, or even a representative part of, the possible range of futures. It is therefore impossible for practical purposes to construct quantitative probability distributions of climate change impacts.

Seeking to quantify the uncertainty in future impacts is in fact only one approach to accounting for uncertainty in water resources management. Another approach, frequently used to represent other sources of uncertainty (*e.g.*, in demand for water), is scenario analysis, based on the use of a small number of coherent scenarios. Robust decision-making (Lempert *et al.*, 1996; 2006) combines features of classic decision analysis and traditional scenario planning. It includes two stages. The first stage essentially involves assessing the performance of a set of defined adaptation actions against a wide range of plausible future conditions. This appears to be very similar to traditional scenario planning, but there are two main differences of emphasis. First, the focus from the beginning is on adaptation options rather than the future scenarios. Second, the approach involves the assessment of option performance against a very large number of scenarios. The second stage uses the information from the assessment of the initial adaptation options to design revised adaptation options. It does this by identifying, for a given adaptation option, the future scenarios which are particularly challenging, and determining the features of those scenarios that cause problems. The adaptation option is then revised to better cope with these features – and the iteration continues. Even if it is not feasible to identify a single robust strategy (i.e. all the options converge following iteration), the approach does enable the presentation of key tradeoffs and allow decision-makers to determine which risks should be addressed. Lempert & Groves (2010) describes an application of this approach to the Inland Empire Utilities Agency, supplying water to a region in southern California. The approach led to the refinement of the company's water resource management plan, making it more robust to the three particularly challenging aspects of climate change identified by the scenario analysis.

[Add text on "climate risk assessment" as applied in water resources management (*e.g.*, as proposed by Freas *et al.*, 2008).]

### *3.6.6. Capacity Building*

Water resources management and development includes processes of water allocation and distribution, water supply and sanitation services, and water infrastructure and procurement. IWRM is based on the principles that fresh water is a finite and vulnerable resource, and essential to sustain life, development and the environment; water development and management should be based on a participatory approach, involving users, planners and policymakers at all levels; women play a central part in the provision, management and safeguarding of water; and water has an economic value in all its competing uses and should be recognized as an economic good. Institutional and local capacities are prerequisites for facilitating adaptation to climate change and are needed to deliver best management practices and education, and to raise awareness. Strengthening leadership, professional capacity, and communication on climate change adaptation is essential to cope with the increasing vulnerability to climate change. Capacity building means to acquire relevant hydrological and climate information, to make use of this information in planning processes through community-based, participatory processes and traditional knowledge, and to acquire financial commitments for adaptation programs. Thus, in implementing successful adaptation measures it is absolutely vital to ensure that local people are properly trained as well as being empowered to manage any instrument or system (*e.g.*, probabilistic decision making tool) that is being set up locally and to transfer technology to low-level water managers. The planning of adaptation projects should be done together with the community to understand the use and methodology of appropriate technologies (Smit and Wandel, 2006; UNECE, 2009; Halsnæs and Trærup, 2009; Olhoff and Schaer, 2010; Bates *et al.*, 2008; von Storch, 2009).

To avoid adaptation measures with negative results "*maladaptation*", intensive research has to precede the planning. Furthermore, Low-regret or No-regret adaptation options, where moderate levels of investment increase the capacity to cope with projected risks or where the investment is justified under all plausible future scenarios, should be aspired (World Bank, 2007).

To improve the capacity in water resources management various initiatives such as the Co-operative Programme on Water and Climate (CPWC) of the UNESCO-IHE Institute for Water Education or the Network for Capacity Building for Sustainable Water Resources Management (Cap-Net) of the UNDP have been launched in order to raise awareness of climate change adaptation in the water sector.

"Adaptation in the water sector involves measures to alter hydrological characteristics to suit human demands, and measures to alter demands to fit conditions of water availability. It is possible to identify four different types of limits on adaptation to changes in water quantity and quality (Arnell and Delaney, 2006).

Finally, the capacity of water management agencies and the water management system as a whole may act as a limit on which adaptation measures (if any) can be implemented. The low priority given to water management, lack of coordination between agencies, tensions between national, regional and local scales, ineffective water governance and uncertainty over future climate change impacts constrain the ability of organizations to adapt to changes in water supply and flood risk" (IPCC AR4 WGII) [to be updated].

## 3.7. Linkages with Other Sectors and Services

### *3.7.1. Impacts of Adaptation in Other Sectors on Freshwater System*

Adaptation in other sectors such as agriculture and industry might have impacts on the freshwater system and have to be considered while planning adaptation measures in the water sector. For example, improving agricultural land management practices can also lead to reductions in erosion and sedimentation of river channels. Some adaptation measures in other sectors may cause negative impacts in the water sector, e.g. increased irrigation upstream may limit water availability downstream (World Bank, 2007). Furthermore, a project designed for other purposes may also deliver increased climate change resilience as a co-benefit, even without a specifically identified adaptation component (World Bank, 2007).

From a socio-economic perspective water has four main functions, i.e. health function (e.g. importance of safe drinking water), habitat function of water bodies (e.g. aquatic ecosystems), carrier function (e.g. erosion, transport and sedimentation of dissolved and suspended material and nutrients), and production function (e.g. agriculture, industry and housing) (Falkenmark, M., 1997; Kuchment, 2004).

Pressures on water resources are increasing mainly as a result of human activity – namely urbanization, population growth, increased living standards, growing competition for water, and pollution. Increasing competition for water is predicted as it is a resource for economic versus ecosystem requirements (UN-Water, 2008; UNEP, 2008; Sadoff and Muller, 2009).

### *3.7.2. Climate Change Mitigation and Freshwater Systems*

Many measures for climate change mitigation have an impact on freshwater systems, while freshwater management may affect GHG emissions. Impacts of climate change mitigation on freshwater systems as well as effects of water management on GHG emissions and mitigation are compiled in Bates *et al*. (2008).

#### *3.7.2.1. Impact of Climate Change Mitigation on Freshwater Systems*

Afforestation on suitable areas following the Clean Development Mechanism-Afforestation/Reforestation provisions of the Kyoto Protocol was estimated to lead to decreases in long-term average runoff. On half of the area, decreases are expected to be less than 60%, while on 27%, runoff decreases by 80-100% were computed, mostly in semi-arid areas (Trabucco *et al*., 2008). Depending on local conditions, runoff decreases may have beneficial impacts, e.g. on soil erosion, flooding, water quality (N, P, suspended sediments) and stream habitat quality (Trabucco *et al*., 2008; Wilcock *et al*., 2008). Economic incentives for carbon sequestration may encourage the expansion of Pinus radiata timber plantations in the Fynbos biome of South Africa, with negative consequences for water supply and biodiversity. Afforestation appears viable to the forestry industry under current water tariffs and current carbon accounting legislation, but would appear unviable if the forestry industry were to pay the true cost of water used by the plantations (Chisholm, 2010).

It was estimated that ethanol from corn and from switch grass requires much more water than other renewable energy sources for the same amount of energy produced, except for hydropower where water is lost from reservoirs be evaporation (Jacobson, 2009). In the USA, 2% of total consumptive water use in 2005 was due to biofuel production, mainly caused by irrigation of corn for ethanol production, with 2400 l consumptive water use per l ethanol (King *et al*., 2010). In two scenarios, this fraction increases to 9% in 2030, but future water consumption strongly depends on the degree of irrigation (King *et al*., 2010). Depending on the region, also biofuel crops like jatropha may require irrigation to achieve satisfactory yields. Energy consumption for pumping water for irrigating jatropha in India was estimated to be so high in case of a pumping depth of 60 m that energy gain by higher crop yields under irrigation is lower than the energy consumption for pumping (Gupta *et al*., 2010). Conversion of native Caatinga forest into castor beans fields for biofuels in semi-arid Northwestern Brazil may lead to a significant increase of groundwater recharge (Montenegro and Ragab, 2010) but there is the risk of soil salinization due to rising groundwater tables.

$CO_2$ leakage from saline aquifers used for Carbon Capture and Storage to freshwater aquifers may lead to a pH decline of 1-2 units and increased concentrations of m*et al*.s, uranium and barium (Little and Jackson, 2010). Pressure buildup caused by gas injection could result in brines or brackish water being pushed into freshwater regions of the aquifer (Nicot, 2008). Displacement of brine into potable water has not been included in a screening methodology for CCS sites in the Netherlands (Ramirez *et al*., 2010).

Hydropower generation leads to fragmentation of river channels and to alteration of river flow regimes that negatively affect freshwater ecosystems, in particular biodiversity and abundance of riverine organisms (Döll, 2009; Poff and Zimmerman, 2010). In particular, hydropower operation often leads to fast sub-daily discharge changes that are detrimental to the downstream river ecosystem (Bruno *et al*., 2009; Zimmerman *et al*., 2010). If, in tropical regions, the ratio of hydropower generation to surface area of the related reservoir is less the 1 $MW/km^2$, the global warming potential ($CO_2$-eq. emissions from the reservoir per MWh produced) can be higher than in the case of coal use for energy production (Gunkel, 2009).

Densification of urban areas to reduce traffic emissions may conflict with provisioning additional open space for inundation in case of floods (Hamin and Gurran, 2009).

#### *3.7.2.2. Impact of Water Management on Climate Change Mitigation*

A number of water management decisions affect GHG emissions. Emissions from peatland drainage in Southeast Asia contribute 1.3-3.1% of current global $CO_2$ emissions from the combustion of fossil fuels (Hooijer *et al*., 2010). Peatland rewetting in south-east Asia would lead to substantial reductions of net greenhouse gas emissions (Couwenberg *et al*., 2010). CC mitigation by the conservation of wetlands will also benefit water quality (House *et al*., 2010). Irrigation has the potential to lead to increased $CO_2$ storage in soils due to enhanced biomass production without water stress. Irrigation in semi-arid California did not significantly increase soil organic carbon but strongly increased soil inorganic carbon if irrigation water was rich in Ca (Wu *et al*., 2008). Water management in rice paddies can reduce GHG emission. If rice paddies are drained at least once during the growing season, with resulting increased water withdrawals, global $CH_4$ emissions from rice fields could by decreased by 4.1 Tg/a (15%), and no significant increase in $N_2O$ emissions would occur (Yan *et al*., 2009).

## 3.8. Water Management, Water Security, and Sustainable Development

Past experience suggest that adaptations is best achieved through mainstreaming and integrating climate responses into development and poverty eradication processes, rather than by identifying and treating them separately (Elasha, 2010). The rationale for integrating adaptation into development strategies and practices is underlined by the fact that many of the interventions required to increase resilience to climatic changes generally benefit development objectives.

Water development, planning processes in light of climate change; uncertainty in future hydrological conditions are well discussed (Bates, B. C., Kundzewicz, Z. W. Wu, S. & Palutikof, J. P. (eds) (2008)). Integrating water resources management on actors, reshaping planning processes, coordinating land and water resource management, recognizing water quality and quality linkages, conjunctive use of surface and ground water and protecting and restoring natural systems have been given priority in water management aspects.

## 3.9. Research and Data Gaps

Precipitation and river discharge are systematically observed, however, the length of historical data record and availability are unevenly distributed in the world, and other physical information related to hydrological cycles, such as soil moisture, snow depth/water equivalent, evapotranspiration, ground water depth, and water quality including sediments are mostly limited in developed countries. Socio-economic data relevant for impact assessments and vulnerability estimations, such as surface water withdrawal and exploitation of ground water by each sector, and autonomous adaptations that have been already implemented to secure stable water supply, are further limited even in developed countries. As consequences of these situations, assessment capabilities are mostly within developed countries, and there are very little peer-reviewed literatures on the observed trends, detections and attributions, projected changes, impacts, vulnerabilities, and possible adaptation options for human-induced climate changes in water sector.

Relatively few results are available on the economic aspects of climate change impacts and adaptation options related to water resources, which are of great practical importance for supporting the decision making on the best mix of mitigation and adaptation in each region. Damage curves that relate the magnitude of hazards, such as precipitation intensity, dryness of surface soil moisture, and storm surge, with the expected human and economic damages are required in each region probably for major causes of water related disasters.

Still there is a scale mismatch between the large-scale climatic models and the catchment scale, which needs further resolution. Water is managed at the catchment scale and adaptation is local, while global climate models work on large spatial grids. Increasing the temporal and spatial resolutions of adequately validated regional climate models and statistical downscaling can produce information of more relevance to water management. Also extreme events that can be simulated with statistical significance either by global or regional climate models are generally not as infrequent as engineering criteria, which is typically 1% to be exceeded annually. Computing capacity will be required to solve these problems by more ensemble simulations with higher spatial and temporal resolutions.

Interactions among socio-ecological systems are not yet well considered in the studies of impact assessments of the climate change. Particularly, there are only a few studies on the impacts of mitigation and adaptation measures for other sectors on water sector, and on the impacts of adaptation measures for water sectors on other sectors. Hydrological models or even land surface component of climate models coupled with anthropogenic activities, such as reservoir operations, irrigation and urban water withdrawals either from surface water or ground water, would help investigating the interactions and projecting the consequences.

_____ START BOX 3-2 HERE _____

**Box 3-2. Case Study: Himalayan Glaciers**

Contrary to the assessment of Cruz *et al*. (2007), it is *very unlikely* that Himalayan glaciers will disappear by 2035.

*Observations*

Observed styles of retreat (reduction of glacier length) vary greatly but it is difficult to isolate a climatic contribution even when multiple measurements are averaged. For example debris-covered glacier tongues are common; they tend to be stagnant and to have stable terminuses, which therefore convey little or no information about climate (Scherler *et al*., 2011). Figure 3-10a summarizes all published measurements of shrinkage (reduction of area). There is no clear pattern of spatial variation, but the measurements sample about one fifth of the total glacierized area and may suggest recent acceleration. It is *unlikely* that the Himalaya-wide average over recent decades was as large as –0.50% $a^{-1}$ (20% in 40 years, a figure often mentioned). The mode of the observed distribution is near –0.10% $a^{-1}$, but the distribution is skewed towards greater rates.

[INSERT FIGURE 3-10 HERE

Figure 3-10: a) Published sub-regional shrinkage rates from the Himalaya–Karakoram. b) Measured mass-balance rates from the Himalaya–Karakoram, updated from Cogley (2009). Glaciological measurements are made annually in situ on the glacier. Geodetic measurements, mostly multi-annual, compare a later map to an earlier one. Each balance is drawn as a thick horizontal line contained in a ±1 standard deviation box (±1 standard error for geodetic measurements).]

For most purposes, the preferred measure of glacier change is the mass balance. Himalayan mass balances, measured by both in-situ annual and multi-annual geodetic methods, have been negative on average for the past five decades (Figure 3-10b). The loss rate apparently became greater after 1995, but it has not been faster in the Himalaya than elsewhere.

Cogley (2011) estimated that total glacier mass in the Himalaya and Karakoram in 1985 was between 4000 and 8000 Gt, well below the 12 000 Gt given by Cruz *et al*. (2007). The analysis relies on volume-area scaling, glacier by glacier. The single-glacier estimates are uncertain by some tens of percent, and are strongly correlated with each other.

More information is now available on the Karakoram anomaly (Hewitt, 2005), an apparent increase of mass balance in the central, highest parts of the Karakoram. The first direct demonstration of slightly positive mass balance in the Karakoram, for 2003–2009, was presented recently by [PLACEHOLDER].

*Projections*

On the basis of volume-area scaling, it is projected (Cogley, 2011) that if the average mass-balance rate of 1975–2008 is sustained, the mass of glacier ice in the Himalaya in 2035 will be 38–62% of its mass in 1985. However, if the rate continued to accelerate as observed during 1985–2008, the percentage remaining in 2035 would be 18–42%. These losses may be exaggerated, because the simulated 1985–2010 shrinkage rates are larger than those observed. Hydrological simulations have obtained satisfactory agreement between model results and limited observations in Himalayan catchments (e.g., Rathore *et al.*, 2009), but the 21st-century projections do not yet present a coherent region-wide picture. Akhtar *et al.* (2008) simulated the discharge of three rivers in northern Pakistan for 2071–2100. Although two models each showed the expected shift of seasonal maximum discharge from summer towards spring, they agreed poorly on magnitudes of discharge decrease. Ren *et al.* (2007) studied the increment of glacier melt water production to be expected under the SRES A1B scenario, finding values of the order of +100 mm $a^{-1}$ by 2025–2030. This, however, was a highly generalized analysis.

Steady or accelerating loss per unit area from a store of diminishing area, such as the Himalayan glaciers, entails a maximum in the total rate of loss: “peak melt water”. Rees and Collins (2006) imposed a warming rate of 0.06 K $yr^{-1}$ and found that peak melt water would be reached in hypothetical glacierized basins around 2050 in the drier eastern Himalaya and around 2070 in the wetter western Himalaya.

*Impacts*

Mass loss from Himalayan glaciers is consistent with observed increases of temperature, and with anthropogenic forcing of the radiation balance. No studies have yet attempted to detect a signal in Himalayan glacier changes that is not explainable by natural variability, or to attribute such a signal statistically to human activities. However, the growing atmospheric burden of dust and soot, much of it of human origin, has received increased attention as a possible driver (Das *et al.*, 2010; B.Q. Xu *et al.*, 2010). Measurements of atmospheric black carbon at 5 km asl in eastern Nepal (Yasunari *et al.*, 2010), and an assumed but conservative deposition rate, imply that the reduction of snow albedo could yield 70–200 mm $a^{-1}$ of additional melt water.

Moraine-dammed ice-marginal lakes in Himalayan valleys continue to give cause for concern (Komori, 2008; Fujita *et al.*, 2009; Ye *et al.*, 2009). Gardelle *et al.* (2011) assessed the growth of moraine-dammed lakes at seven sites along the length of the Himalaya. In western India and Pakistan, lakes were small and stable in size. In Nepal and Bhutan they were more numerous and larger, and most lakes grew between 1990 and 2009; the total lake area increased by 37% in two Nepalese districts. Thus the hazard has increased in magnitude, but there has been little progress on the predictability of dam failure.

Himalayan glacier melt water is at present an increasing, and during this century is likely to become a decreasing, component of a complex mix of sources of freshwater. The population inhabiting glacierized basins around the world is in the billions (Immerzeel *et al.* 2010), but the relative contribution of the glaciers to water resources decreases with distance downstream. The contributions are relatively greatest where rivers such as the Indus enter seasonally arid regions, and become negligible in the downstream parts of monsoon-region basins such as the Ganges–Brahmaputra (Kaser *et al.*, 2011). But, to paraphrase Kaser *et al.*, “strong human dependence on [and vulnerability to] glacier melt [are] not collocated with highest population densities”.

_____ END BOX 3-2 HERE _____

**Frequently Asked Questions**
[to be finalized in the future draft]

FAQ-Ch3-I: What is the most significant new findings on the impacts of climate change on freshwater resources?

FAQ-Ch3-II: What kind of vulnerability was newly revealed in the freshwater resources management during the 21st century?

FAQ-Ch3-III: How water utilities should prepare for CC impacts

FAQ-Ch3-IV What policy makers need to know

FAQ-Ch3-V- What Policy makers need to do

FAQ-Ch3-VI Are the estimation of cost on climate change reliable to decide short and long term investments on infrastructure?

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Table 3-1: Access mechanisms to adaptability.

| Mechanisms | Remarks |
|---|---|
| Technology | Ability to construct water supply and distribution systems |
| Information | Scientific and legal expertise, traditional ecological knowledge |
| Capacity | In determining impacts and developing response measures |
| Institutions | Integrating into national plans and strategies, which cut-across a number of institutions and may need the initiation of new institutions and coordination of comprehensive strategies and ensure sustainability |
| Capital | Insure provision of hardware and software technology and build the technical capacity to deal with adaptation |

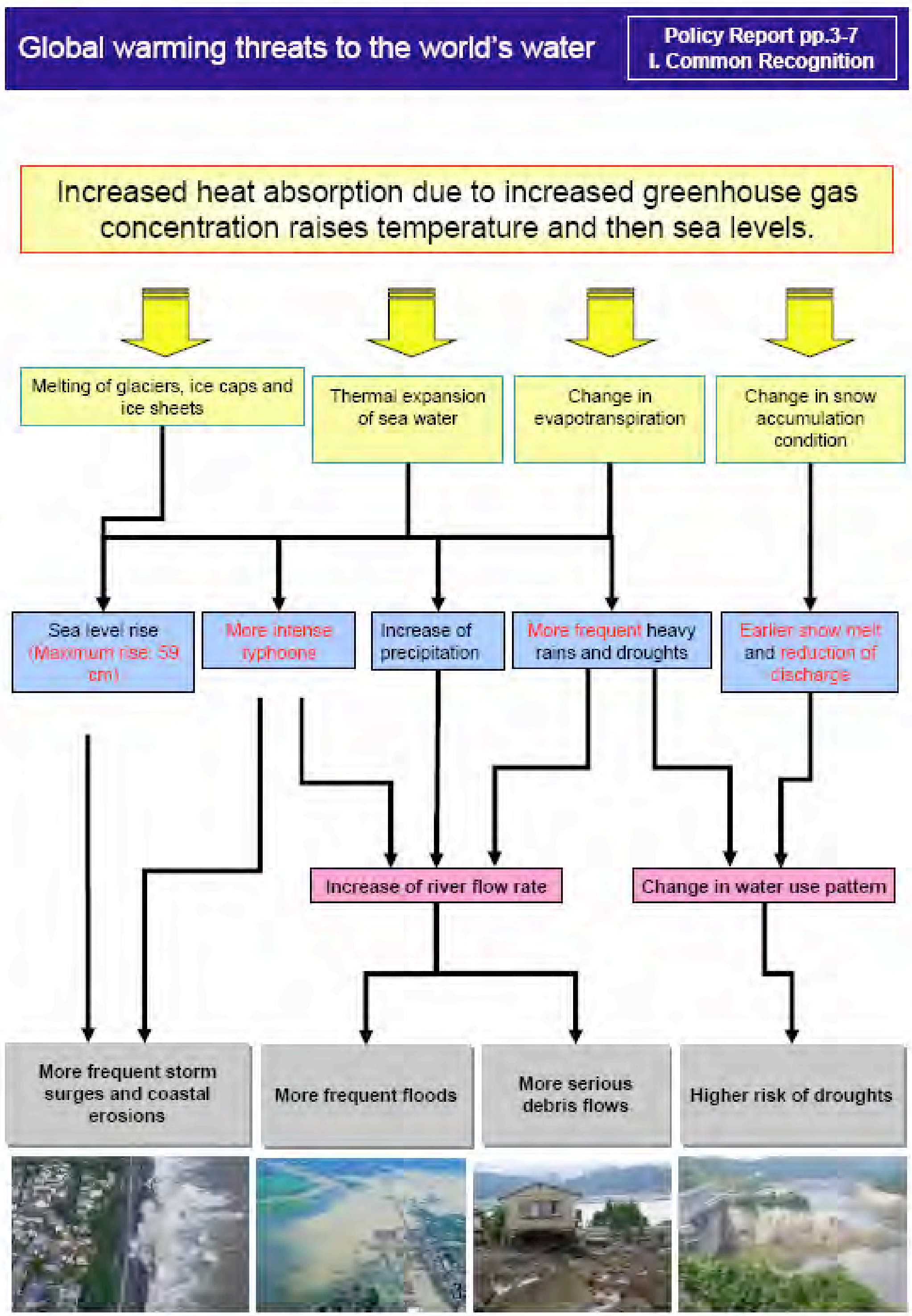


Figure 3-1: This is an example figure and Ch3 Author Team will develop a new figure illustrating the framework.

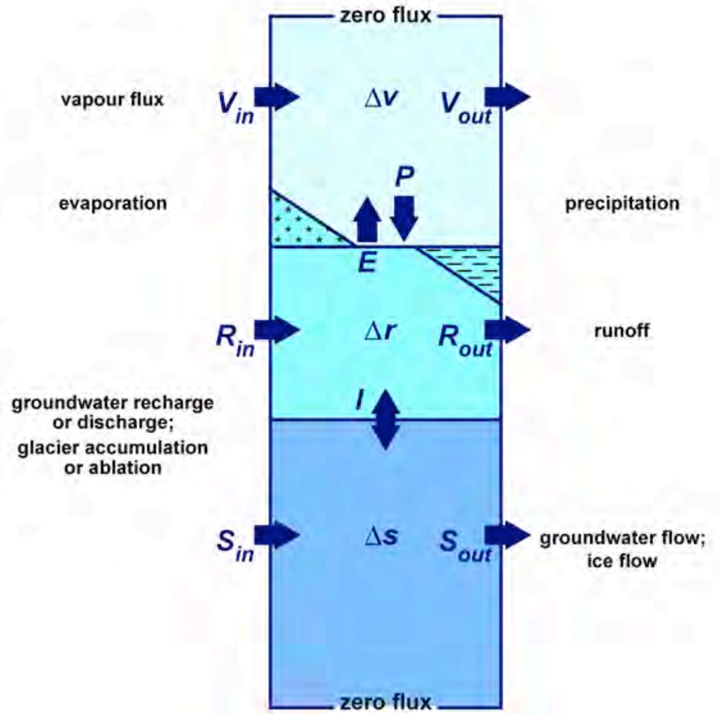


Figure 3-2: Components of the freshwater balance of a vertical column extending through the land-surface hydrological system. Pale blue: the atmosphere. Light blue: the land surface (soil; snow; watercourses, wetlands and lakes). Medium blue: aquifers and glacier ice.

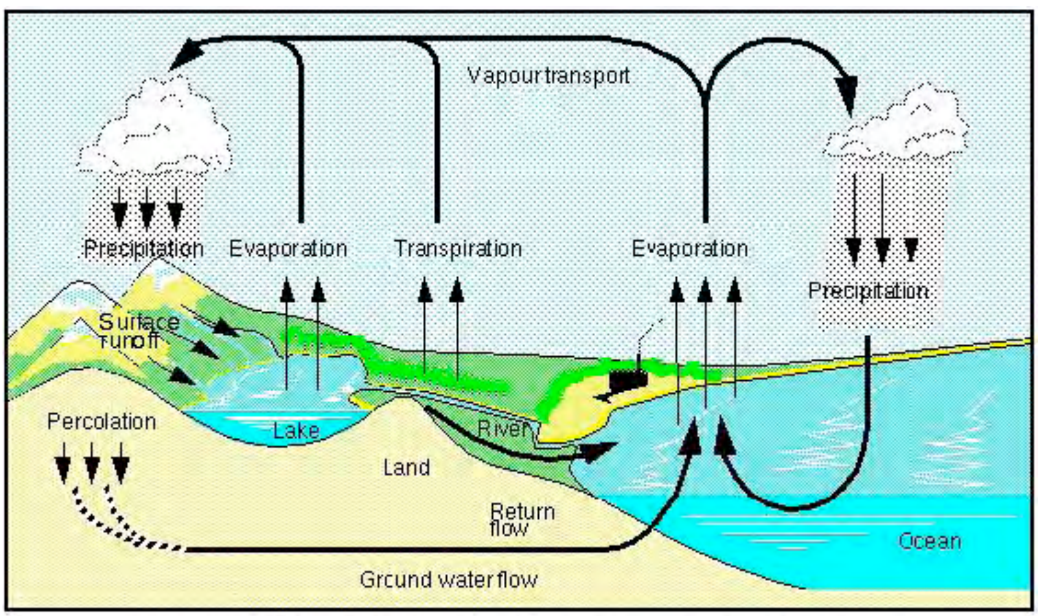


Figure 3-3: Placeholder (Fig. 1 from *WG1 CH12 ZOD, FAQ 12.2*); Ch3 Author Team will develop a schematic of the water balance tailored to the needs of the chapter.

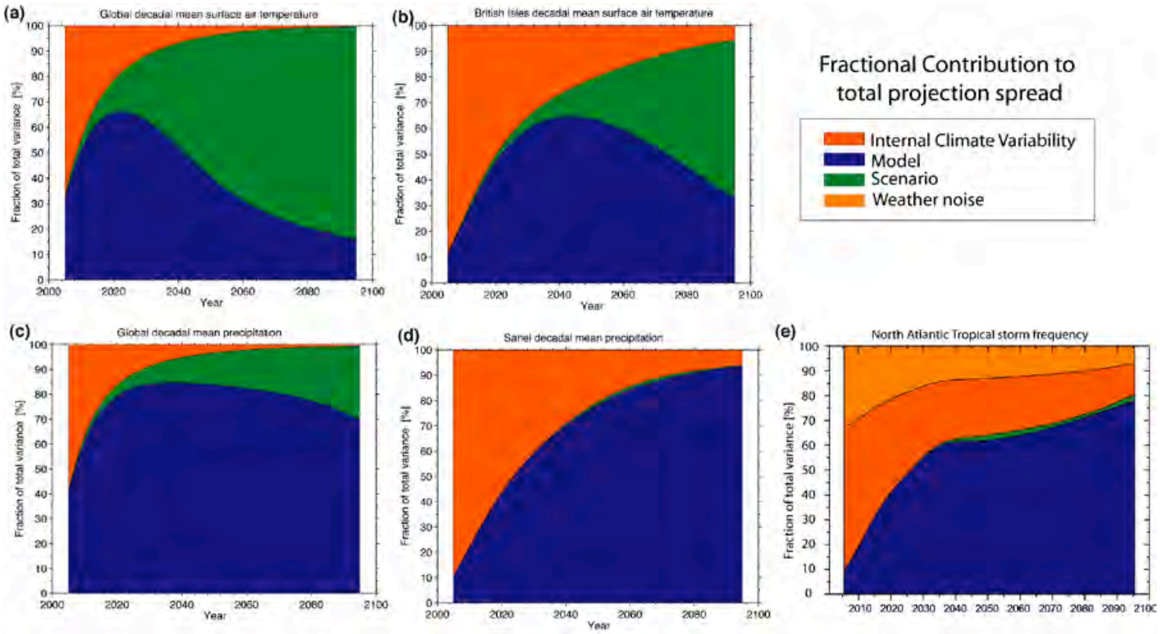


Figure 3-4 [ar5.wg1.ch11.Figure 11.4: included as a placeholder]. The relative importance of each source of uncertainty for decadal mean anomalies (relative to 1986–2005 average) for various quantities is shown through the fractional uncertainty (the 90% confidence level divided by the total uncertainty) based on CMIP3 models. The sources of uncertainty considered are: model uncertainty (blue), scenario uncertainty (green, an estimate of total forcing uncertainty), internal climate variability (orange) and weather noise (yellow in panel "e").

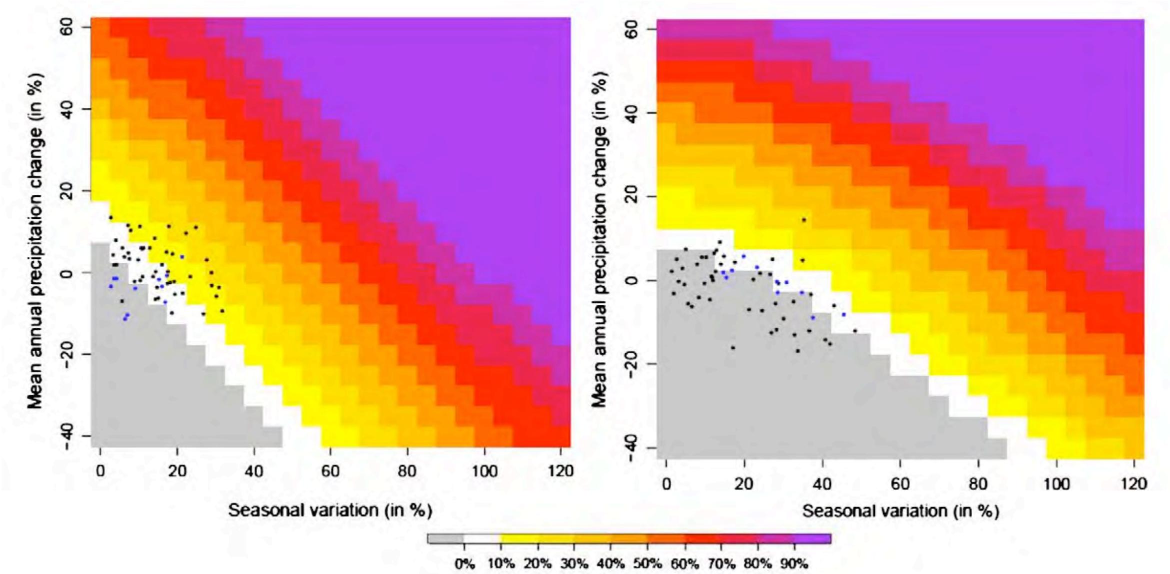


Figure 3-5: Response surfaces showing change in the 20-year flood for two catchments in the UK, for defined changes in the magnitude of precipitation change and seasonal variability in change (Prudhomme *et al.*, 2010). The black dots represent individual climate model scenarios.

**[to be generated]**

Figure 3-6: Map of change in average annual runoff across the global domain (to follow)

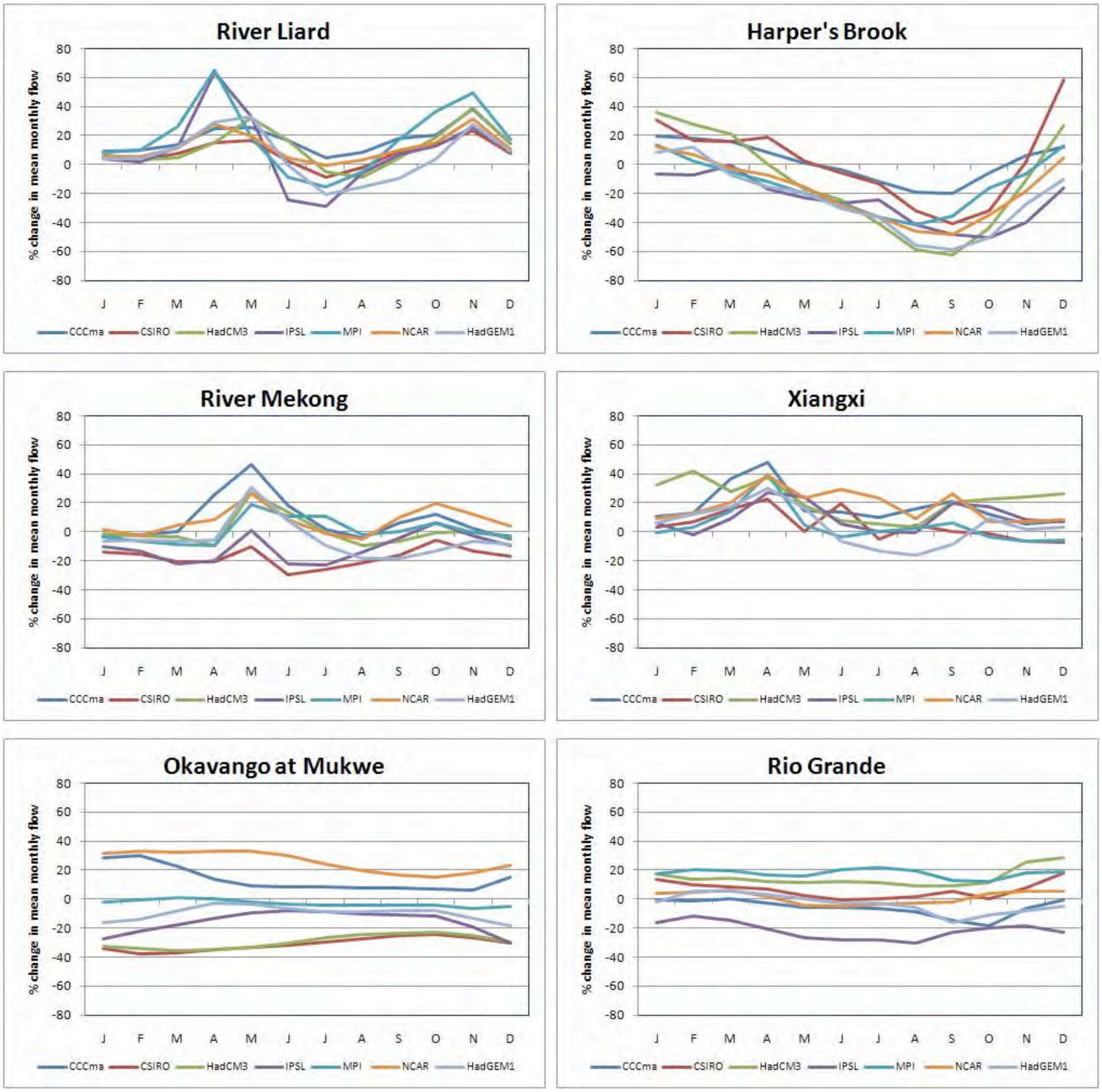


Figure 3-7: Change in mean monthly runoff in 9 catchments, with a 2ºC increase in global mean temperature (above 1961-1990) and seven climate models (to be redrawn): (Hughes *et al.*, 2011; Kingston & Taylor, 2010; Nobrega et al., 2011; Xu *et al.*, 2011; Arnell, 2011b)

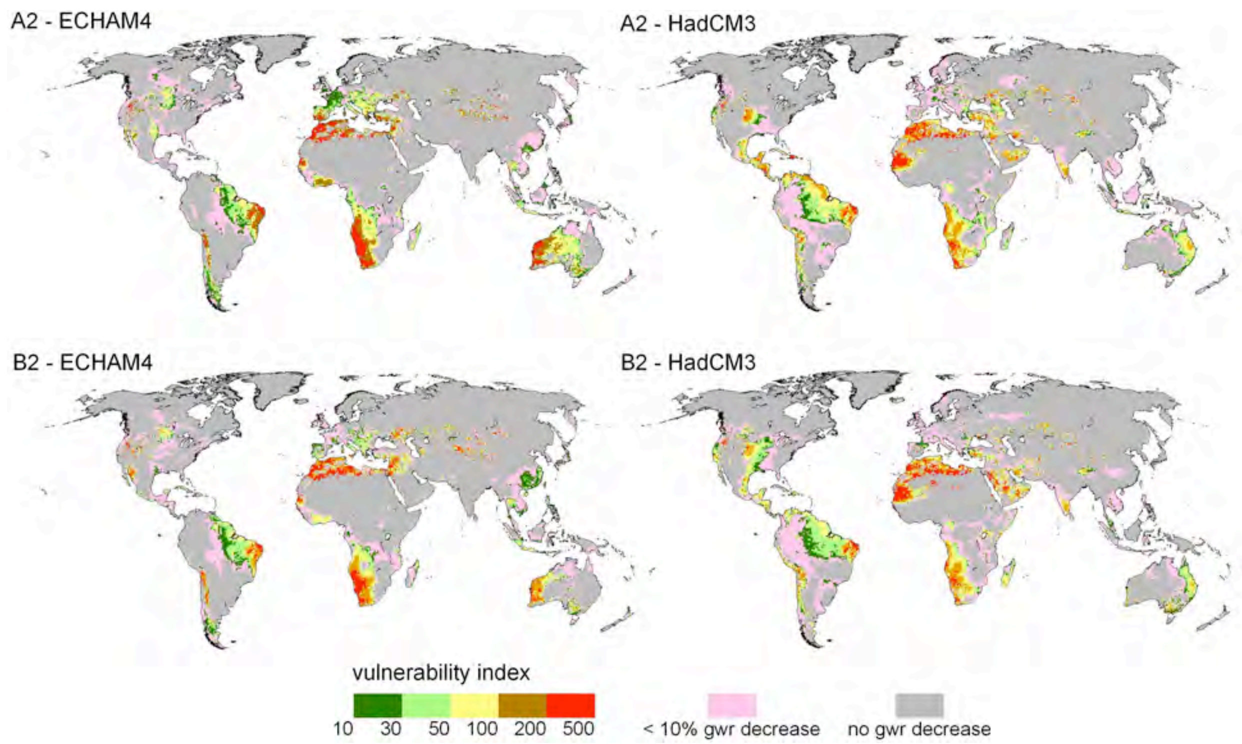


Figure 3-8: Human vulnerability to climate change induced decreases of renewable groundwater resources by the 2050s for four climate change scenarios. The higher the vulnerability index (computed by multiplying percent decrease of groundwater recharge by a sensitivity index), the higher is the vulnerability. The index is only defined for areas where groundwater recharge is projected to decrease by at least 10%, as compared to the climate normal 1961-90 (Döll, 2009).

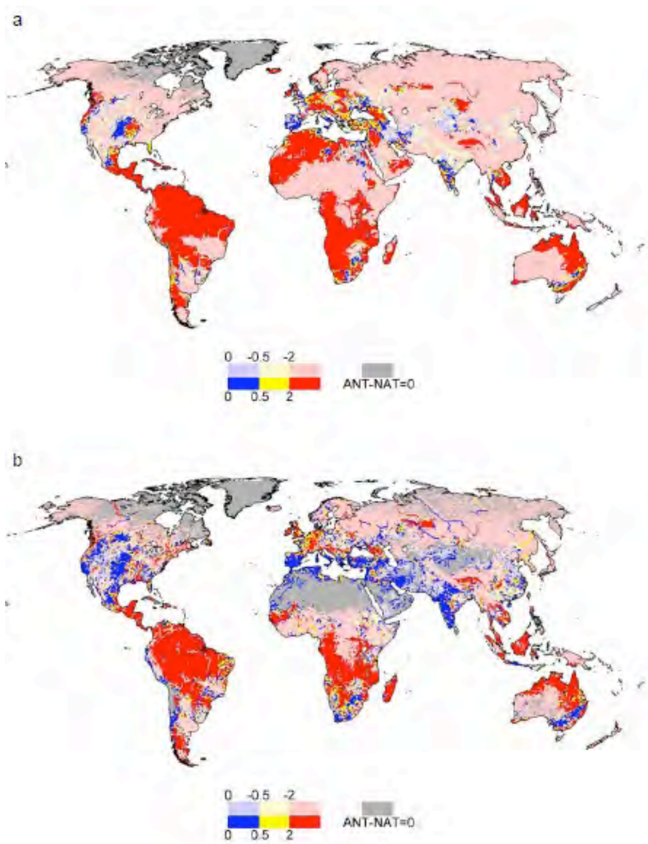


Figure 3-9: Comparison of the impact of climate changes to the impact of dams and water withdrawals for long-term average annual discharge (a) and monthly low flow $Q_{90}$ (b). Red colors indicate that the climate change affects the flow variable at least twice as much as dams and water withdrawals do, blue colors the opposite. Positive values indicate the changes due to climate change and withdrawal and dams are either both negative or both positive. Dams and withdrawals in the year 2002, climate change between 1961-1990 and 2041-2070 according to the emissions scenario A2 as implemented by the global climate model HadCM3.

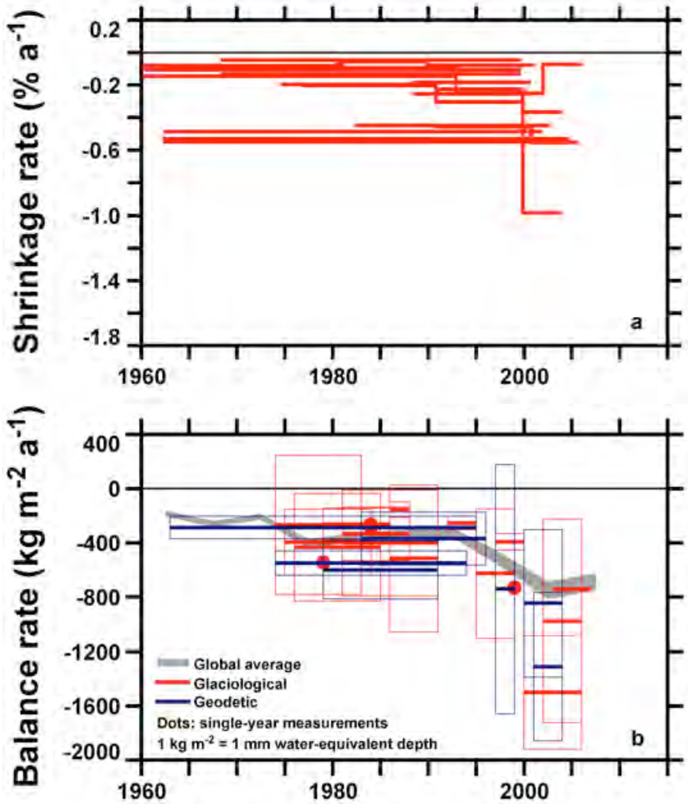


Figure 3-10: a) Published sub-regional shrinkage rates from the Himalaya–Karakoram. b) Measured mass-balance rates from the Himalaya–Karakoram, updated from Cogley (2009). Glaciological measurements are made annually in situ on the glacier. Geodetic measurements, mostly multi-annual, compare a later map to an earlier one. Each balance is drawn as a thick horizontal line contained in a ±1 standard deviation box (±1 standard error for geodetic measurements).