Chapter 3. Freshwater Resources

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Executive Summary

Climate models project both increases and decreases of available water at the regional scale (*high agreement, robust evidence*). Evapotranspiration will increase, and average annual runoff is generally projected to increase at high latitudes and in the wet tropics and to decrease in most dry tropical regions. Reliable surface water supply is likely to decrease in many regions because of decreases in snow/ice storage and groundwater recharge, degradation of water quality, and more variable streamflow due to more variable precipitation. [3.4.2; 3.4.4; 3.4.5; 3.4.6; 3.4.7; 3.4.9; 3.5]

The water cycle is expected to continue to intensify (*high agreement, medium evidence*). Wet regions will get wetter and dry regions will get drier. However the best evidence for intensification is indirect, and is at odds with limited evidence that land-surface evaporation and wind speed have been decreasing. [3.3.1.2; 3.2.2]

Intense precipitation events will become more frequent (*high confidence*) and droughts will become more frequent (*low to medium confidence, medium evidence*). The observed intensification of heavy precipitation events is *very likely* to be anthropogenic. Climate models, however, do not simulate the observed intensification correctly, so that projections may be biased low. Simulated changes in the incidence of droughts are regionally very variable. [3.3.1.4]

Glaciers will continue to lose mass, with peak meltwater flows coming earlier in spring and annual total meltwater yields eventually diminishing as the glaciers shrink (*high confidence, high evidence*). Glaciers would continue to lose mass even if the climate were to cease to change, because they have long response times. The rate of actual mass loss will probably accelerate. The seasonal duration and annual accumulation of snowfall will decrease and the duration and amount of meltwater production will increase. A “meltwater dividend” can be expected during the next several decades, but it will be followed by decreases in the supply of meltwater. [3.4.4.2]

Hydrological impacts of climate change on humans and freshwater ecosystems increase with increasing greenhouse-gas emissions (*limited evidence, high confidence*). Climate change is very likely to impact freshwater ecosystems by changing river flow. This impact is likely to be stronger than the impact of historic river flow alterations due to human water withdrawals and dams. A low-emissions pathway will avoid damage costs and costs of adaptation. [Table 3-2; 3.4; 3.5.]

Certain approaches to reduce greenhouse-gas emissions imply greater risks for freshwater systems than others (*high confidence, limited evidence*). Production of bioenergy crops may require large amounts of water for irrigation and may have negative impacts on water quality. Hydropower has a negative effect on freshwater ecosystems. Carbon capture and storage can decrease groundwater quality. In some regions, afforestation can reduce renewable water resources. [3.7.2.1.]

Water quality changes have been linked to increases in temperature or pluvial precipitation (*medium to high confidence, medium to good evidence*). However, it is still difficult to clearly link them to climate change due to several anthropogenic confounding factors. Despite this, projections under climate change scenarios show (medium agreement, medium evidence) that there is a risk of deterioration of water quality, notably impacting upon the cost of the safe supply of water for municipal purposes. [3.2.5; 3.5.4.1.]

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 have 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: Framework considering the impacts of climate change on freshwater systems and society.]

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. Detection and Attribution

Many hydrological systems have changed in recent decades. A documented hydrological trend, however, is not necessarily a detected impact of climate change. For detection, it must be shown that at least a part of the trend is not due either to non-climatic anthropogenic changes (such as land-use changes or water withdrawals) or to natural random variability of the water cycle as caused by natural climate variability. Hydrological changes can often be attributed confidently to their climatic drivers. Table 3-1 and Figure 3-2 provide examples of detection and attribution. But end-to-end attribution, all the way from human climate-altering activities to impacts on freshwater resources, is not attempted in most studies. That is, they do not formally exclude natural variability as a driver. Natural variations of the water cycle cannot be observed in isolation from external forcing (solar fluctuations, volcanic aerosols, anthropogenic greenhouse gases), and thus can only be assessed in experiments with climate models in which the external forcing is “switched off”. However climate models do not currently simulate the water cycle in sufficient detail for the purpose. Improved integration of climate models and impact models should be a near-term priority (Schiermeier, 2012; PLACEHOLDER REF). In the meantime, it is necessary to rely heavily on multi-step attribution, in which hydrological changes are shown to be consistent with climatic changes that are in turn attributable to anthropogenic or other forcing.

[INSERT TABLE 3-1 HERE
Table 3-1: Observation, detection and attribution of impacts of climate change on freshwater resources
Sources correspond to those in Figure 3-2.]

[INSERT FIGURE 3-2 HERE
Figure 3-2: Confidence in detection and attribution of observed (not projected) impacts of climate change on freshwater resources; see Table 3-1. for further details. Different colours represent different subjects (red: extremes; blue: groundwater; orange: water quality). Filled symbols represent end-to-end attribution of hydrological change to anthropogenic climate change; open symbols represent attribution to climate change. The positions of symbols within grid cells have no quantitative significance.
Caveat: This is a placeholder. The list of studies shown is expected to change.
Caveat: Identical symbols of different colours may cause difficulty for colour-blind readers; this will be worked on.]

3.2.2. 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; Hartmann *et al*., 2013). Gosling *et al*. (2011) found that with increasing global warming increases in the magnitude of the change in annual and seasonal precipitation are found for numerous basins. Significant long-term precipitation changes have not been observed, but according to regional observation data, most droughts and extreme rainfall events of the 1990s and 2000s have been the worst since the 1950s (Baringer *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).

The water-holding capacity of the atmosphere and evaporation into the atmosphere increases with higher temperatures. This favors increases in climate variability, with more intense precipitation and more drought events (Kundzewicz *et al*., 2007; Trenberth *et al*., 2003).

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 this appears to be due mainly to drying of land surfaces rather than to observed reductions of atmospheric evaporative demand (Jung *et al*., 2010). Probably caused by changes in precipitation, (net) solar radiation, vapour pressure deficit (VPD), and wind speed, the rate of regional pan evaporation has been steadily decreasing over the past 50 years (Fu *et al*., 2009; Miralles *et al*., 2011). Fu *et al*. (2009) point out that the magnitude of changes and importance of each of the causes varies from region to region. They conclude that so far no fundamental physical-based explanation has been provided for the so called “evaporation paradox”. Decreasing wind speeds (terrestrial stilling) are globally widespread, helping to explain declines in evaporative demand (McVicar *et al*., 2012). The evaporation paradox is made more puzzling by robust oceanographic observations of changes in geographical patterns of salinity. Salty parts of the ocean are getting saltier and fresher parts fresher (Durack *et al*., 2012), a change attributable only to a more intense water cycle.

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 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). Such findings in drought trends and severity need to be taken carefully, as e.g. Sheffield and Wood (2007) point out that PDSI and other methods give diverging results for droughts. Hirschi *et al* (2011) attributed summer hot extremes in Eastern and Central Europe to prior soil moisture deficits.

Glaciers around the world have continued to lose mass steadily. Mass loss from glaciers has contributed to observed sea-level rise, and it is *very likely* that the contribution from the ice sheets is now substantial and growing (Comiso *et al.*, 2013). Observed trends in the sea-ice cover of the Arctic Ocean are partly explained by external forcing, which in turn shows an increasing anthropogenic signal (Stroeve *et al.*, 2007; Min *et al.*, 2008). As examples of changes on land, fast glacier margin recession, thinning of the ice cover and an increase of regional snowline elevation are observed in South America (Rabassa, 2009). [to be updated when AR5 WGI results are available]

Decreases in the extent of permafrost are widely observed, for example in the Andes (Rabassa, 2009). [More text needed here.]

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). Most climate models project that anthropogenic forcing causes only a small increase in global mean precipitation. But Zhang *et al*. (2007) estimate 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.

3.2.3. 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 human modification (e.g. dams, surface and groundwater withdrawals, deforestation, urbanization) of natural stream flow volumes. Reported in the AR4 (Trenberth *et al*., 2007), regional changes include a stream flow increase 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*., 2001). Recent analysis of river discharge records has 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 reporting a decreasing trend in stream flow for southern and eastern regions, and generally an increasing runoff trend elsewhere, particularly 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 in total runoff 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 runoff trends (statistically significant for the Pacific) and only 19 having an upward discharge trend. Decreases in river discharge may be argued to have a strong human influence whereas increases in annual stream flow are more likely than not dominated by climate (Dai *et al*., 2009). Apart from seasonal and annual precipitation variability, other climate-related factors may affect regional changes on runoff production including soil moisture and evapotranspiration which are linked with catchment vegetation (Peel, 2009). Canopy transpiration may be inhibited an even suppress as stomata openings of many plant species are reduced due to raising anthropogenic emissions (Field *et al*., 1995). This CO_2 physiological forcing on runoff have been invoked as a potential cause of change on global river discharges, and it was detected over all regions at the 5% significance level, and particularly in South America and Asia the model's simulation introducing this forcing is consistent with observed records (Gedney *et al*., 2006; Betts *et al*., 2007).

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 increases, 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), in Finland (Korhonen and Kuusisto, 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*., 2007), or a decrease in spring flood peak in regions with decreased snow cover and amounts (Hirabayashi *et al*., 2008; Dankers and Feyen, 2009). In regions where the lowest mean monthly flow occurs in summer, streamflow has experienced 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 in terms of heavy precipitation there are more locations and studies that show an increasing trend over the late 20th century than those recording a decrease (Seneviratne *et al*., 2012). Reported flood disasters and damages worldwide have been increasing since 1970s (Kundzewicz *et al*., 2007), although this increase may be explained in terms of increasing exposure of people and economic assets (Handmer *et al*., 2012). Cunderlik and Ouarda, (2009) reported a change on flood frequency on snowmelt floods (earlier snowmelt) over the last three decades with significant trends at 20% of stations in SE Canada towards decreasing magnitudes, whereas increasing peak flows were recorded in NW Canada. 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, trends on peak flow follow a similar pattern to the ones detected by Stahl *et al*. (2010) for annual stream flows. In Northern-Western Europe, there is a higher number of gauge stations showing a significant upward trends in flood magnitude and frequency, covering W, S and central Germany (Petrow and Merz, 2009), the Meuse river (France, 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 flood occurrence and no change in summer flooding was reported (Mudelsee *et al*., 2003). In South-western Europe, there is no evidence on generalized trend on annual flow maxima (Renard *et al*., 2008, Benito and Machado, 2012), although regional discrimination (Renard *et al*., 2008) shows a decreasing trend on flood frequency in the Pyrenees, a flood magnitude decreases in the Alps region, in relation with earlier snowmelt processes. British rivers showed significant positive trends in high-flow 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 suggest a higher probability of extreme rainfall events under anthropogenic climate change conditions.

Droughts

In general terms, very dry areas (PDSI < -3) worldwide had augmented its extent from 12 to 30% since 1970s (Dait *et al*., 2004). This increase in the aridity 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 20th century, pointing out towards a strong increase in warm-dry mode over central-southern countries. Shifts in the mean seasonality in hydrological variables may also give rise to episodic anomalous soil moisture conditions. Exceptional low winter precipitation in the UK gave rise to unprecedented dry conditions in spring 2012. 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 19th and 20th 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 (Seneviratne *et al*., 2012). Changes in drought patterns have been reported for 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).

3.2.4. Groundwater

Groundwater is by far the largest reservoir of liquid freshwater, and an attractive freshwater source as it is better protected from pollution than surface water and is available also during dry seasons when rivers carry little or no water (Kundzewicz and Döll, 2009). With approximately 13,000 km^3/yr, renewable groundwater resources amount to one third of the total renewable freshwater resources on Earth (Döll, 2009). Approximately 1,500 km^3 of groundwater were withdrawn for human use each year around the year 2000 (one third of total water withdrawals; Döll *et al*., 2012). Groundwater contributes 42%, 36% and 27% of the water used for irrigation, households and manufacturing (Döll *et al*., 2012). In some semi-arid and arid regions with intensive irrigation, groundwater was depleted by human water use, by an estimated 4,500 km^3 globally between 1901 and 2008 (Konikow, 2011).

Observed changes in groundwater level, storage or discharge are largely attributable to human water withdrawals and other human actions not related to climate change. Attribution to climatic changes is rare. Observed decreases of the discharge of groundwater-fed springs in Kashmir/India were attributed to observed precipitation decreases (Jeelani, 2008; Table 3-1). A model-based assessment of observed decreases of groundwater levels in four overexploited karst aquifers in Spain led to the conclusion that groundwater recharge as a fraction of observed precipitation decrease declined during the 20th century. This allowed an attribution to observed temperature increase which caused increasing evapotranspiration (Aguilera and Murillo, 2009; Table 3-1).

3.2.5. Water Quality

Currently, little information is available with regard to observed changes in water quality attributed to long term climate variability. In addition, most of this refers to surface water bodies and developed countries. Such reports are comprised of the analysis of 10-44 years of historical data on climate and water quality. These are linked at a local level either to seasonal or annual variations in air and water temperature and/or precipitation, unusually warm conditions, extreme rain events, droughts and/or the ENSO phenomenon (Pednekar *et al*., 2005; Tibby and Tiller, 2007; VanVliet and Zwolsman, 2008; Benítez-Gilabert *et al*., 2010; Sahoo *et al*., 2010; Tetzlaff *et al*., 2010; Marce *et al*., 2010; Saarinen *et al*., 2010; Ventela *et al*. 2011). The details of attribution and detection for these studies are presented in Table 3-1. Observed effects have their origin in the increase in water temperature resulting from the atmospheric temperature increase, but also may be attributed to the different hydraulic patterns originating from variations in the pluvial precipitation and the evapotranspiration processes. Reported observations are described separately for surface water (natural or artificial reservoirs and rivers) and for groundwater.

Natural reservoirs

Lakes respond to changes in inflow volumes and water temperature because of modifications in the hydraulic retention time, mixing patterns, solubilization conditions and introduction of pollutants. In addition, changing wind speeds also modify mixing patterns. Numerous studies not linked to climate change have reported tis in the past. Due to their specific characteristics, shallow lakes are more vulnerable to these impacts.

For different lakes in Western Victoria, Australia and California, US, studies of 15 to up to 37 years of historical data (Tibby and Tiller, 2007; Sahoo *et al*., 2010) have reported that the increase in atmospheric temperature was reflected in the increase in both water temperature (high confidence) and nutrient content (medium to high confidence depending on local conditions). Eutrophication, resulting from higher nutrient contents sometimes associated with climate variability, seems to be exacerbated (medium to high confidence) by higher water temperatures and longer residence times, frequently impairing drinking water supplies due to odour and toxicity problems caused by algal blooms (Paerl *et al*., 2006; 2008; Van Vliet and Zwolsman, 2008; Sahoo *et al*., 2010; Qin *et al*., 2010; Trolle *et al*. 2011). Increased storm runoff results in increased nutrient, salinity and fecal coliform (FC) contents. Medium confidence is attributed to the higher content of these pollutants with the exception of fecal coliforms for which confidence is high (Pednekar *et al*., 2005, Paerl *et al*., 2006). Most studies associate the presence of pollutants with a combination of climatic and non-climatic factors. For the three lakes in Western Victoria, extended dry periods or reduced precipitation were also correlated with medium to high confidence to an increase in salinity, measured as conductivity, together with the content of nutrients and some heavy m*et al*s and m*et al*loids with medium confidence (Tibby and Tiller, 2007). In addition, for an artificial reservoir (Sau Reservoir, in Spain) used to manage water supply, stream flow variations were of greater significance than temperature increases in the depletion of dissolved oxygen from water, according to data collected between 1964 and 2007 (Marce *et al*., 2010). One recently reported positive impact on the water quality in an estuary resulted from a study of 30 years of data from the Neuse river Basin in North Carolina. The effect of large storms and hurricanes in flushing previously deposited and stored nutrients reduced the risk of eutrophication and algal blooms (Paerl *et al*., 2006).

Rivers

The variations observed in rivers (Evans *et al*., 2005; Saarinen *et al*., 2010; Benítez-Gilabert *et al*., 2010; Gascuel-Odoux *et al*., 2011; Tetzlaff *et al*., 2010) are all considered negative in terms of water temperature and the levels of sediment, organic matter, pathogens, conductivity, nutrients and acidity (for some Nordic regions). One of the main pollutants reported to impair the quality of drinking water is the organic matter content. This relationship was linked with medium to high confidence, depending on local conditions, to higher precipitation, but also to non-climatic drivers (Evans *et al*., 2005). In semiarid areas, temperature changes in streams are considered more important than precipitation changes 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). Observations made during wet periods, for both wet and arid regions, consistently showed an increased rate of pollution in terms of pathogen contents (high confidence).

Groundwater

With regard to groundwater, elevated concentrations of standard bacterial indicators of pollution were observed during the rainy season or after extreme rain events (high confidence), with time responses varying according to local conditions. This effect can be difficult to detect in different places as it can be masked by other anthropogenic sources of pollution (Howard *et al*., 2003). However, during dry periods, fecal pollution levels were extremely variable, illustrating the need for a better understanding of this phenomenon under such climatic conditions (Tetzlaff *et al*., 2010). Contamination of groundwater drinking supplies during extreme rainfall events has been associated with high confidence to outbreaks of diarrheal diseases in both high and low income countries (Curreiro *et al*., 2001; Tumwine *et al*., 2002; 2003; Auld *et al*., 2004; Jean *et al*., 2006; Taylor *et al*., 2009).

Some general conclusions are (Evans *et al*., 2005; Senhorst and Zwolsman, 2005; Tibby and Tiller, 2007; 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 linking climate variability to water quality should be interpreted cautiously and at a local level as a complex interrelationship exists between climate, hydrology, natural and anthropogenic conditions; (b) the relationship between water quality and climatic parameters is non-linear, except for temperature, and is 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 have been impacted upon in many locations 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 may be found to be inadequate or insufficient to deal with the negative impacts of climate change, depending on local conditions. This last conclusion applies particularly to sites already suffering from eutrophication and where pollution sources from soil erosion, intensive farming practices, and/or municipal and industrial wastewater discharges exist.

3.2.6. Soil Erosion, Sediment Load

Soil erosion on slopes and sediment load in rivers are controlled by climate-related drivers (e.g. rainfall intensity and runoff), and non-climatic drivers (e.g. soil erodibility, vegetation changes, conservation measures), the later depending on land-use and human activities. Many rivers are already under a great deal of stress owing to intensive human action. This stress will further be exacerbated by climate change, thus a better understanding of the past responses of soil erosion and sediment load to climate variability is critical. At secular timescales, climate variability has played a more important role than human impact in driving changes in sediment yield (Walling, 2009). Changes on soil erosion and sediment load are expected as anthropogenic climate change is leading to increased or decreased rainfall amounts and intensities in combination with changes in land use/cover, plant canopy, litter cover, soil moisture, soil erodibility, a shift in winter precipitation from non-erosive snow to erosive rainfall, and melting of permafrost (Kundzewicz *et al*., 2007).

The sensitivity of soil erosion to climate change indicators, such as temperature and rainfall, depends mainly on the combination of runoff and biomass growth response. Therefore, the soil erosion would show significant differences between vegetation types. In southern Italy, erosion measurements in badlands (period 1974-2004) showed a reduction in erosion rates parallel to a steady decrease in annual and winter rainfall amounts (Clarke and Rendell, 2010). In addition, compared with water flow, soil erosion and consequent sediment generation can be more sensitive to climate change (Syvitski *et al*., 2005; Zhu *et al*., 2008). Pruski and Nearing (2002) simulated the response of soil erosion in hillslopes with different soil types to changed rainfall intensities and amounts. In most cases, the soil erosion is highly sensitive to rainfall changes, changing by up to 2.5% for per 1% change in rainfall.

Although there are numerous studies on lake sedimentation and their responses to climate variables (Adrian *et al*., 2009), little work has been done on the effects of climate change on contemporary sediment transport in streams and rivers, mainly due to the difficulties in modeling sediment load and disentangling the impacts of climate change from those associated with humans. Nevertheless, there is a growing body of evidence that climate changes have had a significant impact on the sediment loads of the world's rivers (Walling, 2009). In the temperate and (sub-)tropical regions, some evidences indicate that precipitation changes have resulted in sediment yield changes. For the Yellow River basin where soil erosion is mostly controlled by the magnitude and frequency of heavy rainfall events, climate change has contributed 30-48% to the total reduction in sediment yield due to reduced precipitation during 1970-2008 (Wang *et al*., 2007; Miao *et al*., 2011). Dai *et al*. (2008) qualitatively analyzed the sediment discharge decrease from the Yangtze River to the East China Sea, and found that climate change is responsible for a slight increase in sediment flux of about 3% in the Yangtze River basin. Increased rainfall in the Parana-Paraguay river system in South America has resulted in enhanced soil erosion and inevitably an increase in sediment yield (Amsler and Drago, 2009). Climatic change in tropical regions may be associated with greater intensity and increased frequency of tropical cyclones, which will probably increase soil erosion and consequent sediment flux (Terry *et al*., 2002).

Recent concerns on the potential impacts of climate change on soil erosion and sediment generation are more associated with regions of high altitude or latitude. Glacial rivers are characterized by high sediment flux and accelerated ice-melting may result in even higher sediment loads. In these regions, global warming is expected to significantly enhance soil erosion intensity and sediment generation. Under a warming climate, permafrost thaw and degradation will trigger a series of hydrological and geomorphologic changes. Due to climate change, rapid glacial recession has been reported for the rivers originating from the Himalayas and Tibet Plateau (Li *et al*., 2008). Recent investigations indicated that glacier areas in China have shrunk about 2-10% over the past 45 years (Li *et al*., 2008). As these glaciers are melted, the initially protected soil surfaces and the sediments within the glaciers will be exposed to erosion and transport. Aan increasing trend in sediment load in the headwaters of the large Asian rivers Yangtze River has been reported (Lu *et al*., 2010). Using sediment volume delivered by a glacier located in southern Patagonia Andes, Fernandez *et al*. (2011) evaluated its erosion rates across different timescales. Their results showed that the averaged soil erosion rate increased from 5.3 mm/yr for the last 364 years to 29.3 mm/yr for the last 45 years. In polar regions, significant increase in soil erosion rate due to climate change has also been detected. The mean annual soil erosion rates in Arctic Alaska have increased from 6.8 m/yr during 1955-1979 to 8.7 m/yr during 1979-2002, and to 13.6 m/yr during 2002-2007 (Jones *et al*., 2009).

3.2.7. 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.]

3.2.8. 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 evaporative demand, which is the ability of the atmosphere to draw water from a fully wet surface. (Evaporation itself varies with the wetness and roughness of the surface as well.) 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 expressed 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.

Among other potential climatic drivers are atmospheric carbon dioxide, which can affect evaporation via its physiological control of transpiration (evaporation by plants), and deposited black carbon and dust (see Box 3-2). Both of the latter, in even very small concentrations, enhance melting of snow and ice markedly by reducing the surface albedo.

_____ START BOX 3-1 HERE _____

Box 3-1. The Freshwater Balance

The freshwater balance is an equation in which all the transfers of fresh water across the boundary of a defined volume containing part of the Earth's land surface are added up over a given span of time and stated to be equal to the change of water storage within the volume. The transfers and the change of storage are expressed as either totals (for example in m^3) or rates (for example in mm of equivalent water depth per month or per year) as illustrated in Figure 3-3. The water balance of the surface excludes aquifers and the atmosphere, and when there are no substantial lakes, wetlands or glaciers the annual change of storage in the soil is often assumed to be zero. In this case the surface water balance is simply the sum of precipitation, evaporation and runoff. However, changing soil moisture may be of concern over longer periods. In the context of water resources, changes of storage in aquifers, lakes and wetlands, glaciers and seasonal snow packs can also be of prime importance.

[INSERT FIGURE 3-3 HERE
Figure 3-3: Global hydrological fluxes (1000 km^3/year) and storages (1000 km^3) with natural and anthropogenic cycles are synthesized from various sources. Big vertical arrows show total annual precipitation and evapotranspiration over land and ocean (1000 km^3/year), which include annual precipitation and evapotranspiration in major landscapes (1000 km^3/year) presented by small vertical arrows; parentheses indicate area (million km^2). The direct groundwater discharge to the ocean, which is estimated to be about 10% of total river discharge globally, is included in river discharge. (Oki and Kanae, 2006)]

_____ END BOX 3-1 HERE _____

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. Internal variability and variation between models account for all of the uncertainty in precipitation near the beginning of CMIP3 projections over the 21st century (Figure 3-4). The contribution of internal variability is initially dominant but diminishes progressively. As the scenarios diverge, they contribute more to total uncertainty but, at least for precipitation, never become dominant. By no later than mid-century, discrepancies between the models account for most of the total uncertainty in precipitation, but the uncertainty in temperature (Kirtman *et al.*, 2013) is due mostly to divergent scenarios. 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: Fraction of variance in projections of changes in decadal-mean precipitation for boreal summer (JJA), decomposed into contributions from three sources of uncertainty. Simulations were for 2000–2100 under the SRES A1B, A2 and B1 scenarios, with a single ensemble member taken from each of 14 CMIP3 GCM experiments. From Hawkins and Sutton (2011).]

The need to downscale the output of climate models makes a further contribution to uncertainty about the hydrologic impacts of the climatic drivers at the drainage-basin scale.

3.3.1.3. Projections

Some 21st-century projections of the climatic drivers of the freshwater cycle yield findings that emerge repeatedly from most or all analyses of most scenarios and that are consistent with accepted understanding of hydrological processes. The commonest features of CMIP3 simulations of the water cycle during the 21st century, with constraints from 20th-century observations, can be summarized (based mainly on Collins *et al.*, 2013) as follows.

- Surface temperature, which affects the water cycle by affecting the vapor-carrying capacity of the atmosphere and the evaporation rate, increases more (by about twice as much) over land than over the ocean (*high confidence*).
- Warming is greatest over polar regions and much greater over the Arctic (*high confidence*) than the Antarctic, implying spatial variation of changes in the timing, duration and amount of snowmelt and the mass budgets of glaciers. However models underestimate the observed polar amplification.
- 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; 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. Precipitation changes become statistically significant only when temperature rises (relative to 1900–1929) by at least 1.1 –1.4°C, and by more in many regions (Mahlstein *et al.*, 2012).

Projected signals that are more uncertain but nevertheless fairly clear 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.

3.3.1.4. Extremes

A warmer climate and more intense hydrological cycle are expected to bring more intense extreme precipitation events, or equivalently more frequent events of any given large magnitude (Field *et al.*, 2012). One proposed reason for more intense precipitation events is their tendency to “empty” the atmospheric column of its precipitable water, which is projected to increase as described in section 3.3.2. (Collins *et al.*, 2013). Another is a proposed increase in the intensity of convective updrafts, which accompany most heavy thunderstorms.

Annual maxima of 24-hour precipitation amounts which had return periods of 20 years in 1981-2000 are projected to have return periods roughly three times shorter in 2081-2100 (Kharin *et al.*, 2007). The projected return periods are shorter for the SRES emissions scenarios A1B and A2 than for the B1 scenario, in which CO_2 concentrations rise by less. Agreement between GCM-simulated extremes and extremes observed in reanalyses is 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.

The observed intensification of large-magnitude precipitation events is *very likely* to be anthropogenic, although there are details that remain obscure (Min *et al.*, 2011). For example the GCMs do not simulate the observed intensification adequately. It is *very likely* that global anthropogenic greenhouse gas emissions increased the risk of flooding in England and Wales in autumn 2000 (Pall *et al.*, 2011).

GCM-simulated changes in the incidence of droughts vary widely, so that there is at best *medium confidence* in projections (Nicholls *et al.*, 2011). Regions where droughts are projected to 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 21st century, distinguishing 11 world regions. The assumed CO_2 emissions of the Policy Reform and Great Transition scenario are below the very low emissions scenario RCP 2.6, while Fortress World and Market forces are between RCP 8.5 and RCP 6.0 (Raskin *et al*., 2010). While the RCP 2.6 trajectory relies on massive deployment of carbon sequestration, 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).

3.4. Projected Hydrological Changes

Generally, hydrological changes are evaluated by comparing possible future hydrological conditions to historical conditions. These projected changes are helpful indicators for understanding human impact on nature and for supporting adaptation to climate change. However, for supporting decisions on climate mitigation, it is more helpful to compare hydrological changes that may occur under different future GHG emissions scenarios. Examples of studies that assess hydrological changes and water-related impacts of climate change under different emissions or global warming scenarios are compiled in Table 3-2.

[INSERT TABLE 3-2 HERE
Table 3-2: Hydrological changes and freshwater-related impacts of climate change on humans and ecosystems that could be avoided with reduced greenhouse gas emissions.]

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. Most have applied a now-standard methodology, using information from climate models to perturb a baseline weather record and a hydrological model to simulate river flows, recharge or water quality. Methodological advances have included the use of multiple climate scenarios and of regional climate models, evaluation of uncertainty due to downscaling, and evaluation of the contribution of hydrological model uncertainty to uncertainty in projected impacts.

Most climate change impact assessments have been based on the use of a small number (five or fewer) of climate 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 and global climate models (Kling *et al*., 2012; 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 (see Section 3.6.5) 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; Christierson *et al*., 2012). 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.

Most hydrological impact assessments have used a catchment hydrological model with the ‘delta-method’ to create catchment-scale scenarios, applying projected changes in climate derived from a climate model either to an observed baseline or with a stochastic weather generator. An increasing number of studies (e.g. Fowler and Kilsby, 2007b; Kling *et al*., 2012; Veijalainaen *et al*., 2012) have run catchment models with input weather data produced by applying some form of bias-correction to regional or global climate model data (van Pelt *et al*., 2009; Piani *et al*., 2010; Yang *et al*., 2010), adjusting the simulated model baseline weather to match the variability in the observed baseline; 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 few studies (e.g. Falloon and Betts, 2006; 2010; Hirabayashi *et al*., 2008) have examined river runoff as simulated directly by a high-resolution climate model; because no bias-correction is applied, the pattern of variability in absolute simulated runoff across space is driven by the simulated precipitation, although the simulated change in runoff should be more consistent with the changes as simulated using a hydrological model off-line. However, this has not yet been systematically evaluated.

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*., 2007a). 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; Quitana 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*. (2007a) 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.

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, 2011b; Lawrence and Haddeland, 2011; Teng *et al*., 2012). 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 are 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 occuring 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 change in rainfall and the hydrological indicator is change in the magnitude of the T-year flood. Climate scenarios from specific climate models can be plotted on the response surface.

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).

Probably caused by changes in precipitation, (net) solar radiation, vapour pressure deficit (VPD), and wind speed, the rate of regional pan evaporation has been steadily decreasing over the past 50 years (Fu *et al*., 2009; Miralles *et al*., 2011). Fu *et al*. (2009) point out that the magnitude of changes and importance of each of the causes varies from region to region. Based on literature review, they conclude that so far no fundamental physical-based theory has been provided to explain the so called “evaporation paradox”.

Another approach to quantify evapotranspiration under changing climates is presented by Serrat-Capdevila *et al*. (2011). They used field observations (from January 2003 to December 2007), 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. In the period of 2000-2100, 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).

An important source of uncertainty in hydrological projections is the response of empirically estimated PET to climate change. Kingston *et al*. (2009) investigated the response of six different methods (Penman-Monteith, Hamon, Hargreaves, Priestley-Taylor, Blaney-Criddle and Jensen-Haise) of estimating PET to a 2°C rise in global mean temperature simulated by the priority subset of 7 GCMs. All methods suggest an increase in PET associated with a warming climate. However, differences in the PET climate change signal of over 100% are found between the methods. This uncertainty is several times that (20 to 40%) of observed between these methods over the baseline period (1961-1990). A 2°C rise in global mean temperature is projected to lead to an overall increase in arid areas but a decrease in humid areas of the global land coverage (Kingston *et al*., 2009).
(cross-reference needed with AR5 WGI and SREX Ch3)

3.4.3. Soil Moisture and Permafrost

Projected changes in spatial patterns of soil moisture are resulting from anticipated changes in precipitation, evaporation, snow melt and runoff characteristics. AR4 WG1 showed multi-model mean changes in soil moisture between 2080-2099 and 1980-1999 for the A1b scenario, showing systematic decreases in the subsidence zones where reductions in precipitation and increases in potential evaporation are coincident (particularly Southern Europe and central America, Southern Africa) and Siberia (see also Seneviratne *et al*, 2010). Similar analyses are ongoing using the CMIP5 modelling archive. Lowere soil moisture values give rise to increased risk of extreme hot days (Seneviratne *et al*, 2006; Hirsch *et al*, 2011) or heat waves. Sheffield and Wood (2008) analysed projected changes in drought occurrence and duration in the AR4 climate model data set. For a range of analysed scenarios, doubling in areal extent and frequency of low soil moisture episodes of 3-6 month duration are found, Frequency of long term droughts (>12 months) is three times more common, particularly in the areas with projected reductions in soil moisture. Large natural variability in drought occurrence and intensity make the generally monotonic increases statistically not different from current climate.

3.4.4. Glaciers

3.4.4.1. 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. These details can vary greatly from basin to basin, and may change with time in ways that have not been studied. Incorporating glacier-specific energy-balance schemes into climate models, thus eliminating the need to do off-line hydrological calculations based on model temperature outputs, has yet to be attempted. The task is challenging because the glaciers usually occupy only a small fraction of the GCM grid cell, their topography and elevation ranges differ greatly from those of the model, and the lapse rate of glacier surface temperature differs in general from that in the free atmosphere (Gardner *et al.*, 2009).

3.4.4.2. Hydrological Impacts of Glacier Mass Loss

All projections for the 21st century (Church *et al.*, 2013) show continued mass loss from glaciers, at scales ranging from single glaciers (Brown *et al.* 2010) to the globe (Radić and Hock, 2011). The seasonal distribution of meltwater runoff in glacierized catchments differs from that in snow-covered catchments, reaching a maximum during 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.* (2010) among many others. Huss (2011) showed that, even in large basins draining the European Alps, the relative importance of high-summer glacier meltwater can be substantial (e.g., 25% of August discharge in basins with area 10^5 km^2 and only 1% glacier cover); high-summer water supply will therefore be reduced noticeably at regional scales by the projected glacier shrinkage to only 12% of 2008 extent by 2100.

The relative importance of the glacier meltwater resource also increases during droughts and anticyclonic heat waves, as in Europe in summer 2003. Again, sustained mass loss diminishes the resource progressively.The other leading glacier-hydrological response to warming is an expected peak in the total annual production of meltwater from stored glacier ice. If warming proceeds at a constant rate then, as meltwater production $B(t)$ per unit area increases in agreement with understanding of the energy balance, and as total glacierized area $S(t)$ decreases in agreement with observations of past glacier behavior, $B(t) \times S(t)$ passes through a maximum: “peak meltwater”. Xie *et al.* (2006) assumed warming rates of 0.02 and 0.03 $\mathrm{K\ a}^{-1}$ 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* that the date of the peak response to 21st-century warming will fall within the century in most inhabited glacierized regions. In many such regions the populace is at present consuming a transitory “meltwater dividend”.

In real glacierized basins, variable climatic forcing leads to complex interannual and longer-term variations of both B and S, and peak meltwater production can be difficult to identify. Of two periods with comparable rates of warming and shrinkage in the European Alps, discharge was significantly greater in the earlier, culminating in the 1940s, than in the later, culminating at the present day (Collins, 2008). There is *medium evidence* that rivers draining the Cordillera Blanca, Peru, now exhibit decreasing annual and especially dry-season discharge because glacier shrinkage has outstripped meltwater production per unit glacier area (Baraer *et al.*, 2012).

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 glaciers shrink, however, their influence on interannual variability diminishes, which may make the water supply 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; Döll and Zhang, 2010; Fung *et al*., 2011), and some assessments have used directly the output from a high-resolution global climate model (Hirabayashi *et al*., 2008; Tang and Lettenmaier, 2012) (Figure 3-5). The projected changes 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. [Cross reference to WG1 to be included here]. Across most of the world, the relationship between change in temperature and change in runoff is approximately linear (Tang and Lettenmaier, 2012), but there are exceptions in some dry regions with small increases in temperature (Tang and Lettenmaier, 2012). Changes in runoff are typically between 1 and 3 times as large as changes in average annual precipitation (Tang and Lettenmaier, 2012).

[INSERT FIGURE 3-5 HERE
Figure 3-5: Map of percentage change of future river discharge (2080-99 average relative to 1980-99 average) simulated by MIROC5 under RCP 4.5 (left) and RCP 8.5 (right) scenarios. (Okazaki *et al*., 2012)]
(They are the results of single GCM, and they will be replaced with those of multi-GCM.)

Figure 3-6 shows change in mean monthly runoff for seven catchments across the globe, under the same seven climate model patterns scaled to represent an increase in global mean temperature of 2°C above the 1961-1990 mean (Hughes *et al*., 2011; Kingston and Taylor, 2010; Kingston *et al*, 2011; Nobrega *et al*, 2011; Thorne, 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. This uncertainty is largely driven by differences in projected changes in precipitation between different climate models.

[INSERT FIGURE 3-6 HERE
Figure 3-6: Change in mean monthly runoff in seven catchments, with a 2°C increase in global mean temperature (above 1961-1990) and seven climate models: (Hughes *et al*., 2011; Kingston and Taylor, 2010; Kingston *et al*., 2011; Nobrega, 2011; Thorne, 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

Projected groundwater recharges (i.e. renewable groundwater resources) and other groundwater-related variables, are, like other hydrological variables, 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). Ensemble studies of the impact of climate change on groundwater recharge and partially also groundwater levels were done for the semi-arid Murray-Darling Basin in Australia (Crosbie *et al*., 2010) and all of Australia (Crosbie *et al*., 2012), a study site in the semi-arid part of the USA (Ng *et al*., 2010), a very humid aquifer at the Pacific coast of the USA and Canada (Allen *et al*., 2010), for aquifers in temperate Belgium and England (Goderniaux *et al*., 2011; Jackson *et al*., 2011) and for the German Danube basin (Barthel *et al*., 2010). The number of applied climate models ranged from 4 to 20, and with one exception, only one emissions scenario, mostly SRES A2, was taken into account. Due to the uncertainty of climate models, the range of future groundwater changes was large, from significant decreases to significant increases for the individual study area (e.g. between -26% and +31% until the 2080s, Jackson *et al*., 2011). For the Belgium aquifer and the German Danube basin, declines of 4-21 m by the 2080s and by 10±3 m by 2060, respectively, were computed.

When considering a particular climate scenario, land areas where total runoff are projected to increase (or decrease) roughly coincide with the areas where groundwater recharge is projected to increase (or decrease) (Kundzewicz and Döll, 2009) but changes in precipitation intensity will change the groundwater recharge fraction of total runoff. Increased precipitation intensity, for example, may decrease groundwater recharge due to exceedance of infiltration capacity (in humid areas) or increase it due to a fast percolation through the root zone from where water otherwise would be evapotranspired (in semi-arid areas) (Liu, 2011; Kundzewicz and Döll, 2009; Owor *et al*., 2009).

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 CO_2), 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 a fully coupled vegetation and variably saturated hydrological model. The resulting increased 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).

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 longer growing periods; there, groundwater recharge may increase due to increased return flows of irrigation water (Toews and Allen, 2009).

Coastal groundwater is affected by climate change not only due to changes in groundwater recharge but also due to sea level rise which, together with groundwater recharge and the rate of groundwater pumping, determines the location of the saltwater/freshwater interface. While most confined aquifers are expected to be unaffected by sea level rise, most unconfined (water table) aquifers are expected to suffer from saltwater intrusion and a loss of freshwater volume (Werner *et al*., 2012; Masterson and Garabedian, 2007). In water table aquifers, the water table very often cannot rise freely with the rising sea water level, for example because groundwater discharges to streams, or because it approaches the soil surface and is evapotranspirated. For each meter that the groundwater table is decreased relative to the sea level, the depth of the freshwater decreases by approximately 40 m (Werner *et al*., 2012). In aquifers with high hydraulic conductivity to groundwater recharge ratio, salt water intrudes further inland in response to a certain sea level rise than in aquifers with lower ratio but it may take several centuries to reach equilibrium (Webb and Howard, 2011). However, even small rates of groundwater pumping near the coast are expected to lead to stronger salinization of the coastal groundwater than sea-level rise during the 21st century (Ferguson and Gleeson, 2012). For a shallow aquifer at the Mediterranean coast of Morocco, the main impact of climate change was estimated to be a decrease of renewable groundwater resources due a decline of groundwater recharge. Groundwater salinity was modelled to sharply increase in within the first kilometre off the current coastline in the future due to sea level rise and groundwater recharge, and it was estimated that further inland salinity may increase due to accumulation of the dissolved salts caused by the with lower flow velocities (Carneiro *et al*., 2010). In the permeable Israeli coastal aquifer, 1 m of sea level rise in 100 years was found be slow enough for groundwater equilibrium conditions to prevail, and the fresh-saline water interface would be shifted only 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 was computed to be 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 may increase by 40% of sea-level rise by the year 2100 (Oude Essink *et al*., 2010). Further inland, land subsidence due to continued land drainage, with peat oxidation and clay shrinkage, may lower groundwater levels, and stronger upward seepage of saline deep groundwater may increase salinization of the shallow groundwater and the surface waters (Oude Essink *et al*., 2010). Regarding vulnerability of coastal groundwater, water table aquifers of flat (coral) islands and delta regions are expected to suffer very strongly from saltwater intrusion due to sea level rise or potentially decreasing groundwater recharge. The latter are negatively affected not only by lateral saltwater intrusion but also by storm surges that result into increased upstream transport of saline waters in the rivers which then contaminate the underlying fresh groundwater from above (Masterson and Garabedian, 2007).

Changes in groundwater recharge also affect streamflow in rivers. In a catchment of the Upper Nile basin in Uganda, increased potential evapotranspiration as occurring under at high global temperature increases of 4°C or more 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

The impact of climate change on water supply affects different sectors and different users (the environment also considered as a user), through a complex set of mechanisms working in parallel and in series, which are perhaps interrelated (Figure 3-7). Thus, modeling actual and future conditions are a difficult task involving the integration of different specific models used to analyze the transportation and transformation of pollutants in water, soil and air in isolated or combined matrices. In addition, such models are not always adapted to local conditions or reliably calibrated due to a lack of sufficient and appropriate data. There is little in the literature on water quality projections linked to climate change scenarios, and where such data is available the uncertainty displayed is high as it results from the accumulation of the uncertainties of the different models used in series. Most projections assessed for the current and previous reviews concur with high confidence that both atmospheric temperature increase and changes in pluvial precipitation affect water quality by affecting water temperature (and effects on associated aquatic biochemical reactions), and by increasing or reducing flows, together with water residence time and the flow velocity.

[INSERT FIGURE 3-7 HERE
Figure 3-7: Complexity of the interactions on different factors impacting water quality.]

Natural and Artificial Reservoirs

Watershed and lake projections at a local level, carried out using different scenarios and models (details shown in Table 3-2), show that an increase in temperature results in a reduction in mixing patterns, leading in some cases to eutrophic conditions depleting dissolved oxygen, solubilizing phosphorus and heavy metals from sediments, and causing algal blooms (Marshall and Randhir 2008; Qin *et al*., 2010; Loos *et al*., 2009; Whitehead *et al*., 2009; Sahoo *et al*., 2010; Trolle *et al*., 2011). Simulations also suggest that in order to control eutrophication, nutrient loads need to be reduced greatly. This requires the combination of different adaptation options (including a reduction in the use of fertilizer and the treatment of wastewater) than would be required under scenarios which ignore climate change (Trolle *et al*., 2011; Marshall and Randhir, 2008; Whitehead *et al*., 2009). In addition, the higher flows expected during part of the winter and/or early spring, at sites where climate change is expected to influence conditions, would tend to increase the loads of sediment, nutrients (N and P loads, with unpredictable N:P ratios) and organic matter. Combined with warmer temperatures, this would lead to a reduction in the dissolved oxygen content and a further deterioration in water quality (Brikowski, 2008; Marshall and Randhir, 2008; Ducharne, 2008). For one artificial reservoir in the Netherlands, projections have shown that an increase in air temperature of 2°C rather than 1°C would lead to a 43% increase in the number of days for which the maximum allowable limit of chlorides is exceeded by 2050 (Bonte and Zwolsman, 2010).

Rivers

Under a range of UKCIP scenarios, it was found (Cox and Whitehead, 2009) that dissoved oxygen in the River Thames will decrease by the 2080s due to increased BOD (biochemical oxygen demand) and the direct effects of temperature, reducing the saturation concentration of oxygen. Associated with this, the frequency and intensity of algal blooms would be expected to increase. For the upper Kennet River system, in southern England, Nitrate-N concentrations, released from diffuse or point source of pollution, would be diluted to a lesser extent due to reduced flows in summer over the 21st century under a range of GCMs (A2 emissions) (Whitehead *et al*., 2006b; 2009).

Groundwater

Although arid and semiarid regions, home to about one fifth of the world’s population, rely largely on groundwater, little research has been performed to assess the future impacts of climate change on its quality (IAH, 2011). Studies in Switzerland of the transport of pathogens in karstic or shallow aquifers showed higher concentrations of pathogens under projected extreme rain events and a reduction in their content during hot and dry summers; in an aquifer in the Netherlands an increase in pluvial precipitation was found to result in higher but variable contents of nitrates in a shallow aquifer (Butscher and 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; Whitehead *et al*., 2009; Kundzewicz and Krysanova, 2010): (a) local conditions; (b) climatic and environmental assumptions, such as other types or sources of pollution and their future evolution; and (c) current impacts (i.e., the present state of deterioration of the studied water bodies), most of which are dynamic and anthropogenic in origin. In addition, for both reservoirs and rivers, even though greater nutrient contents are projected under certain climate scenarios it is difficult to define possible future eutrophication events as these depend on a combination of factors, including nutrient availability, light conditions, temperature, residence time and flow conditions.

Based on the literature review, it can be concluded that it is highly probable that it will be necessary to further control both non-point and point sources of pollution to maintain the quality of water under future climate change scenarios (Marshall and Randhir, 2008; Butscher and Huggenberger, 2009; Whitehead *et al*., 2009).

3.4.8. Soil Erosion, Sediment Load

Future climate change is expected to affect the extent, magnitude, and frequency of soil erosion and sediment flux in response to increasing erosive power of rainfall, changes in plant biomass, and shifts in land use to accommodate the changed climate regime. The extent to which climate change will affect soil erosion will vary widely in scale and intensity in different areas around the world, depending on their vulnerability and adaptive capacity. However, it seems that in most regions climate change will deteriorate soil erosion and increase sediment load in rivers.

Climate change is likely to affect the sediment load in rivers mainly through soil erosion processes, water discharge, and changes in land use and land cover. For example, the increased precipitation and consequently increased water discharge in rivers were projected to increase annual suspended sediment by 17% and 27% in two Danish rivers during the period 2071-2100, but by about 9% and 24%, respectively, if an increased growing season was incorporated (Thodsen *et al*., 2008). In Northern Ireland, Mullan *et al*. (2012) used the Water Erosion Prediction Project (WEPP) model to estimate the impacts of future climate change on soil erosion. Compared with present-day baseline erosion rate, the largest soil erosion rates could increase by 628%, 606%, and 481% for the 2020s, 2050s, and 2080s, respectively. Goode *et al*. (2012) analyzed the enhanced sediment delivery in western North America, and estimated that the climate-driven increases in wildfires had the potential to generate sediment yields approximately tenfold the observed during the 20th century. By means of a one-dimensional sediment transport model (TUGS) and a climate-driven hydrological model (HydroTrend), Gomez *et al*. (2009) projected the changes in water flow and suspended sediment flux in the Waipaoa River in New Zealand. They found that climate change may reduce the mean flow by 13% in the 2030s and 18% in the 2080s. Accordingly, the annual suspended sediment flux changed ±1 Mt/yr by the 2030s, but it may either decline by 1 Mt/yr or increase by 1.9±1.1 Mt/yr by the 2080s. The large variability reveals that complex responses of sediment production to climate-driven changes. For instance, the warmer climate can also promote vegetation growth in some temperate regions, which has the potential to offset the adverse impacts of climate change on sediment load (Gomez *et al*., 2009). Therefore, projecting future sediment flux in response to climate change needs also to consider the sensitivity of land use and land cover to climate change.

According to Trenberth *et al*. (2007), an average annual precipitation increase of 10-30% in the Tibet Plateau by 2080 is projected. Such increases in total precipitation amount, along with glacial melting, permafrost degradation, and the shift of precipitation patterns from snow to rainfall, will further increase soil erosion and sediment loads of the rivers which are currently fed mainly by glaciers (Lu *et al*., 2010). In a major headwater basin for the Ganges River, Neupan e and White (2010) simulated the responses of sediment load that resulted from an increased precipitation and enhanced melting of glaciers, showing an increase sediment yield of 26% by 2050. In the tropical regions, the intensity of stronger storms from cyclones was projected to increase 2-11% by 2100 (Knutson *et al*., 2010), corresponding sediment loads are expected to increase more given their disproportionately high erosive power.

Although intense rainfall events can contribute a disproportionate amount of erosion relative to the total rainfall contribution (Kundzewicz *et al*., 2007), it does not necessarily indicate that the increased frequency of intense storms will produce higher soil erosion rates. Using a revised Morgan-Morgan-Finney erosion model and the regional climate model of HadRM3H in central Europe (Austria) during 2070-2099, Scholz *et al*. (2008) found that, although with seasonal shifts of rainfall amount between 10-14%, the intra-annual precipitation change resulted in a net decrease of rainfall amounts in erosion sensitive months and an overall increase of rainfall in a period in which agricultural areas were less prone to erosion. Consequently, the predicted soil erosion rate under the scenario of the IPCC SRES A2 declined in all tillage systems by 11-24%.

Assessing future impacts of climate change has to take into account the effects of land management measures. In central Europe, compared with the conventional tillage system, the conservation tillage systems reduced soil erosion rates by 41-87% (Scholz *et al*., 2008). Similar soil erosion reductions caused by differences in land management are also reported in other regions of the world. Li *et al*. (2011) assessed the site-specific impacts of climate change in the readily erodible Loess Plateau, China, on soil erosion. Under conventional tillage, the GCMs model projected a soil erosion of -5-195% during 2010-2039. In contrast, the conservation tillage could decrease soil erosion by 26-77% over the same period.

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 3-13) 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 3-11 and 3-12). 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 3-13).

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 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). 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 2^{o}C 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 2°C, however, the climate change effect dominates changes in future resource availability (Fung *et al*., 2011)]. Third, climate mitigation policy only avoids a small proportion of the impacts of climate change on water resources (Fischer *et al*., 2007; Hayashi *et al*., 2010; Arnell *et al*., 2011: Table 3-2). Depending on indicator, a climate policy which achieves a 2°C 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 4°C, and avoids between 15 and 47% by 2100 (Arnell *et al*., 2011).

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 (Kundzewicz and Döll, 2009). 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. Water for Energy Power Production

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. Municipal Water Services

In many parts of the world, municipal water service providers are already experiencing challenging situations and are looking for options to better manage water. In this context, climate change initiatives can be of assistance by providing political drivers and even financial support for projects. It is therefore of interest to better understand impacts, vulnerabilities and risks to be able select, wherever possible, optimal adaptation measures that work under changing scenarios.

3.5.4.1. Municipal Water Supply Services

These are intended to supply all types of settlements (urban, periurban and rural). In cities, besides supplying households, the water network serves businesses and industries. Proper management of municipal supply involves linking water availability (in quantity and quality) to water demand needs.

Water availability

Conventional water sources will experience variations in quantity and quality which, combined with competition for water resources among users, will result in a different situation in the future with regard to the actual availability of water. To illustrate the complexity of this situation under climate scenarios, the analysis carried out by UK water companies is described (Arnell, 2004; Arnell and Delaney, 2006; OFWAT, 2009). Under the climate change UKCIP02 scenario, winter river flows are slightly increased by the 2020s, but summer flows are reduced by up to 30% in the south and east of England. There are indications that groundwater recharge will also be reduced. The actual deficiency in municipal supply depends also on the variations in future water demand and competition with other users. Future demand estimated for different scenarios - depending on regional population, future economic growth, the change in per capita water use and the implementation of control leakage programmes - results in changes between 1997 and 2025 of between –36 and +61%. The second major driver of change in supply is the need to sustain higher flows for ecological purposes. This is to be increased in the UK by 5% by 2025. The use of revised methods to assess the yields of supply schemes can also lead to changes in the calculated supply-demand balance. Recalculations in 2004 by water supply companies of their estimates of deployable output led to increases of up to 5% for some companies and, at the other extreme, a reduction of 16% for another.

Under different climate scenarios, water utilities must consider the following situations (Bates *et al*., 2008, Zwolsman *et al*., 2010; Bonte and Zwolsman, 2010; Mukhopadhyay and Dutta, 2010):

a) Snow and glacial melting -Snow packs and glaciers serve as water storage systems. Their reduction or disappearance represents the loss of storage capacity and hence the need to add artificial storage to continue to match water availability to demand.
b) Shifts in water flows -Differences in river flows will also result in the need for greater artificial storage capacity. In dry climates, shifts might be even larger due to the expected reduction in precipitation, since

drier soils take up more water before any net runoff occurs. Increased evaporation resulting from higher temperatures in natural basins will also reduce the net water production, similarly necessitating increased storage capacity. Groundwater recharge associated with river run off will also be reduced.

Restrictions which may be imposed on water availability due to reduced quality, include the following (VanVliet and Zwolsman, 2008; Jiménez, 2008a ; Brooks *et al*., 2009; Qin *et al*., 2010; Bonte and Zwolsman; 2010; Zwolsman *et al*., 2010; Fenner and Thorne, 2011; Dipankar *et al*., 2011:

a) Higher water temperatures -Besides affecting the rate of biochemical reactions important to an ecosystem's health, more frequent and intense algal blooms and associated cyanotoxic compounds are expected in reservoirs, and not all countries are prepared either to detect or to control them. There have been many cyanobacteria-caused illnesses and even deaths of humans and animals have been reported, not only in developing countries but also in developed ones. Contemporary geographical expansion and increases in the frequency and magnitude of cyanobacteria-related incidents necessitates the identification of their causes and formulation of management strategies to ensure the long-term availability of safe drinking water supplies. Warmer conditions may also lead, directly or indirectly, to long-term changes in the quantity and character of natural organic matter. Many utilities in the northeastern US and northern Europe have noted increases in raw water colour and levels of disinfection by-products (especially haloacetic acids) due to the increased presence of organic matter in water.
b) Drier conditions -Reduced amounts of water result in a lower dilution capacity for pollutants such as nitrates, chlorides, and organic matter, amongst others. Additionally, dryer conditions lead to an increase in the extraction of water from already overexploited aquifers, increasing pollution due to iron and manganese (in India, for instance), arsenic (already a relevant problem in South East Asia and Latin American countries), fluoride (a critical problem in several countries in South East Asia, Africa and some countries in Latin America; Brunt *et al*., 2004), salinity (in coastal aquifers and in areas with certain agricultural practices notably India and North African countries) and nitrates.
c) Higher storm runoff -In rivers and lakes, additional runoff will flush higher loads of pathogens, N, P and turbidity into water bodies from point and diffuse sources of pollution. The indicators traditionally used to assess faecal pollution (faecal bacteria) may be insufficient to track pathogens.
d) Sea level rise and drier conditions -Salinisation of groundwater in coastal and inland aquifers caused by rising sea levels and associated with lowers recharge rates and poor land use practices, will limit accessibility to cheaper water for drinking purposes.

In comparative terms, surface water has always been considered more vulnerable to water quality deterioration than groundwater, and in addition less reliable in terms of both quantity and quality. Nevertheless, in the future, there is a risk that groundwater resources will become more vulnerable both in quantity and quality, due not only to different climatic conditions but also the irrational pattern of use to which they are being subjected worldwide.

Water Treatment

With respect to safe supply, many drinking water treatment plants are simply not designed or equipped to handle extreme water quality variations that exceed design thresholds and potentially necessitate different infrastructure requirements for periods of one month or more per year. Merely to control higher turbidity that would interfere with the disinfection process, higher coagulant doses would be needed, producing higher sludge volumes to be disposed of, and resulting in increased treatment costs that not all utilities may be able to afford (Zwolsman, *et al*., 2010). For groundwater treatment, higher microbiological contents are to be expected and, depending on dilution conditions, nitrates also. For the problem of pathogens, Schwartz *et al*., (2000) and Emelko *et al*., (2011) showed that associated with the daily fluctuations in drinking water turbidity, there was an increase of about 10% in hospital admissions for gastrointestinal illness in elderly people in the US, even when water was filtered in compliance with US standards. Depending on the extent of the changes and the site-specific water treatment processes, poor quality raw water may ultimately result in elongated stoppages of intakes. More dramatically, at sites where no water treatment works currently exist or where they exist but function poorly due to a lack of economic resources (such as in rural or periurban areas), higher rates of water-borne diseases would be expected to be observed (Dipankar *et al*, 2011).

3.5.4.2. Sanitation Service

Sanitation is usually taken to refer to sewerage which manages pluvial water and wastewater, together with wastewater and sludge treatment facilities and the means to dispose of treated or non-treated waste to the environment. For rural, dispersed or low-income urban areas, sanitation is usually limited to the safe handling of excreta and grey water (Jiménez, 2011). While in developed countries sanitation coverage is close to 99%, in developing countries it is only around 50% and comprises infrastructure which does not always adequately function (WHO-UNICEF, 2006). So far, the impacts of climate change on sanitation services have been almost exclusively explored by water utilities in the urban context, considering wet and dry weather conditions as described by NACWA (2009) and Zwolsman *et al*. (2010).

Wet weather conditions
The design of urban drainage systems, based on critical "design storms" defined through analysis of historical precipitation data is to be reviewed under future scenarios. Heavy rainstorms may challenge the present capacity of sewerage systems because of the need to deal with large amounts of pluvial water, and even wastewater in combined systems, over a short period of time. Urban floods have been increasingly reported in several cities around the world, and are a result of a complex set of anthropogenic mechanisms among which land use and the "heath island effect" play a major role in the risk of accentuated patterns of extreme rain events. Possible effects of sea level rise include inundation of brackish or salty water, necessitating the treatment of greater volumes of water to a higher level. Infrastructure system failures may result from higher groundwater levels or high storm surge levels. In addition, many wastewater systems are designed to allow flow by gravity to the discharge point. Rising downstream levels may require the pumping of water to discharge through outfalls, thereby increasing the energy demand.

Dry weather conditions
Water mains and sewers are structurally challenged by drying and hence shrinking soils, so they can crack, leading to increased infiltration and exfiltration, which in turn exacerbates treatment and groundwater or stormwater contamination problems. The increase in corrosion of sewers - due to the combined effects of higher temperatures, increased concentrations, longer retentions times, and stranding of solids - shorten asset life and increase maintenance costs.

Wastewater treatment
Cities suffering from higher storm-runoff need to treat combined sewer overflows (CSO), and an increased amount and variety of pathogens (less sensitive to reduction because of dilution as they are measured in log terms). Under drier conditions, a high content of pollutants in wastewater, of any type, is to be expected and has to be dealt with. This might not be feasible in low income regions (Jiménez, 2011; Dipankar *et al*., 2011), therefore the amount of polluted wastewater to be disposed of may increase. At the present time, despite improvements in some regions, water pollution is on the rise globally, and more than 80% of the municipal wastewater in developing countries is discharged untreated into water bodies or to the ground (World Water Assessment Programme, 2009).

3.5.4.3. New Challenges to Manage Water Services

From the perspective of policy makers and water utilities, the challenges which must be faced are related to protecting water sources in terms of quantity and quality terms, in order to ensure a reliable supply in sufficient quantity; to manage the increased competition for water among users; to deal with water supplies in variable quality and quantity; to protect and repair water infrastructure from hurricanes and floods; and to convince the government to allocate additional funds to accomplish the above mentioned tasks. In addition, the following situations will also need to be addressed (Zwolsman *et al*., 2010; Browning-Aiken, 2006; Jiménez 2011; Jiménez in press; Whitehead *et al*., 2009):

a) Providing water services to increasing numbers of migrants forced to move because of climate change impacts, and other man-made or natural disasters in different countries.
b) Providing services to poor communities that are highly vulnerable and are living in areas where, from a technical perspective, it is very difficult and costly to provide proper services (slums and rural settlements).

c) Dealing with the impact on water services from a rapidly urbanizing world. To date, there have been few studies that explicitly consider water impacts in urban areas under conditions of climate variability and change.
d) Taking care of the growing groundwater issues that are threatening the supply of municipal water in many countries.

Adaptation options

Among the strategies that can be adopted to better assimilate changes in the water and sanitation services the following should be considered (Seah, 2008; Jiménez and Asano, 2008b; Kundzewicz and Krysanova, 2010; Zwolsman *et al*., 2010; Sprenger *et al*., 2011; Jiménez 2011; Emelko *et al*., 2011):

a) Adopting the "waterflex" concept, in which utilities rely on a variety of different water sources rather than a single one.
b) Increasing storage capacity, including that provided by the subsoil.
c) Defining a portfolio of inter-complementary, no regret solutions to provide water supply and sanitation services.
d) Increasing the efficiency of use of water and urgently and dramatically reducing water loses throughout the network
e) Implementing water safety plans to protect water from source to tap.
f) Augmenting the supply of water through reuse and recycling and taking advantage of unconventional water sources for supply (pluvial water, sea water, etc.).
g) Installing and enhancing the operation of water and wastewater treatment plants to deal with variations in influent, and coupling water treatment infrastructure to natural and resilient treatment process such as river bank filtration for drinking water and wetlands for wastewater.
h) Using green urban infrastructure to better manage runoff (such as pluvial collection on household roofs and avoiding transport infrastructure avoiding runoff).
i) Protecting and strengthening water infrastructure to resist hurricanes.
j) Changing the concept of disposing of wastewater (treated or non-treated) to one in which is the aim is to reintegrate water to the environment in order to be used once again.
k) Improving water quality monitoring programs and using water quality models to aid managers' decisions.

3.5.5. Freshwater Ecosystems

Freshwater ecosystems are comprised by biota (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 3.2.5) 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). 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).

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).

Because biota are often adapted to a certain level of river flow variability, the larger variability of river flows that is due to increased climate variability is likely to select for generalist or invasive species (Ficke *et al*., 2007). A high-impact change of flow variability is a river flow regime shift, , from intermittent streams to perennial or vice versa, which may occur, in semi-arid regions, until the 2050s, on 5-7% of the global land area depending on the climate model and the emissions scenario (comp. Table 3-2, Döll and Müller Schmied, 2012).

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 3-9 bottom, 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 3-9). 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 may also provide opportunities for operating dams and power stations to the benefit of riverine ecosystems. This is the case if total runoff increases and, like in Sweden, the annual hydrograph becomes more similar to variation in electricity demand, i.e. with a lower spring flood and increased run-off during winter months (Renofalt *et al*., 2010).

[INSERT FIGURE 3-9 HERE
Figure 3-9: Ratio of the impact of future climate change to the impact of current dams and water withdrawals for long-term average annual discharge (a) and monthly low flow Q90 (b). Red colors indicate that the impact of climate change on the flow variable is at least twice as strong as the impact of dams and water withdrawals, blue colors the opposite. Intensive colors indicate that both drivers lead to the same direction of change of the flow variable, while soft colors the opposite. 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 (Döll and Zhang, 2010)]

3.5.6. Floods

There is high confidence that absolute socio-economic losses from flood disasters are increasing, although attribution of these flood impacts to anthropogenic climate change has not been established (Handmer *et al*., 2012). There is high agreement, but medium evidence that the increases in losses is due to higher exposure of people and assets in at-risk areas, in many cases modulated by soci*et al* factors directly related to population and economic growth (Changnon *et al*., 2001; 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 (Bruce, 1999; 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 (Bouwer, 2011). Most of these studies dealing conclude on the lack of climate change induced trends on the normalized losses (Barredo, 2009; Hilker *et al*., 2009; Benito and Machado, 2012), although some studies did find recent increases in losses related to flood hazards in China (Fengqing *et al*., 2005) and Korea (Chang *et al*., 2009). The general approach of these normalize loss studies is however at country level and not considering the regional flood hazard diversity that is detected on some systematic trends on flooding derived from long-term peak flow records (see section 3.2.2.). 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; Jiang *et al*., 2005, Miller *et al*., 2008, Changnon, 2009). The lack of evidence that anthropogenic climate change has led to increasing risks applies mainly to developed countries where detail inventory of weather-related loss data are available over time. Moreover, robust evidence that anthropogenic climate change has led to increasing losses cannot be attained as far as changes on peak flows are regionally detected, which may required longer observational records or future risk projections that include exposure and vulnerability changes (Fowler and Wilby, 2010, Bouwer, 2011). In developing countries, high uncertainty in the climate change role on increasing flood risk is mainly related to lack of quality and completeness of longitudinal loss data, and to the impacts of modest weather and climate events on the livelihoods and people of informal settlements and economic sectors (Handmer *et al*., 2012). The impacts of local weather extremes are 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, tourism etc. (Badjeck *et al*., 2010; Beniston, 2012; Koetse and Rietveld, 2009; Pinter *et al*., 2006; 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; Buhaug *et al*., 2010; Marshal *et al*. 2009; Solomon *et al*., 2011).

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, 2012).

3.6. Adaptation and Managing Risks

Since the 4th IPCC assessment report, and in some cases since the 3rd, many efforts have been made to identify options for adaptation in the water sector. Many of them are or were applied as a response to climate variability. The water sector has always been a challenging sector, and adaptation to climate change provides many opportunities for improvements that are known as “no regret” actions, which is to say that they are able to generate net social and/or economic benefits regardless of whether climatic change occurs. Table 3-3 summarizes the main adaptation options reported in the literature. A comparison of their cost and complexity is also given. Further details of the adaptation measures can be found elsewhere.

[INSERT TABLE 3-3 HERE
Table 3-3: Climate change adaptation options regarding freshwater.]

3.6.1. Introduction (including IWRM)

Adaptation changes in the hydrological system and water resources are of utmost interest to avoid adverse impacts (such as floods and droughts) to the economy (e.g. economic losses) and in particular the society (e.g. affected population). With increasing temperatures, predictions of future precipitation suggest regional increases or decreases of water availability by 10% up to 40% (Gosling *et al*., 2010). 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, can be helpful in reducing the vulnerability. 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). (cross-reference needed with AR5 WGI and SREX Ch3)

To lessen the aforementioned vulnerability, a crucial role in achieving a sustainable preservation of worldwide water resources lies in their strategic management. This could be done by an incorporation of water-related climate change adaptation schemes into planning, and an implementation of adaptation measures with the application of 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).

Requirements for Integrated Water Resources Management

Climate change and the concomitant increase of extreme events with massive consequences for human populations, economic assets and critical physical infrastructures have exposed weaknesses in current water management. This has increased the awareness of uncertainties, the complexity of the systems to be managed, and the need for profound changes in policy and management paradigms, as well as governance systems (Pahl-Wostl, 2007; Opperman *et al*., 2009). Prospects of climate change render the conditions under which management has to perform increasingly unpredictable and undermines thus key assumptions on which water management has been based (Milly at el, 2008; Bates *et al*, 2008). Major structural changes are needed in all domains of the water sector.

The debate on climate change adaptation has been slow in adopting these fundamental Insights. Much of the debate has centred on developing individual strategies for individual impacts. Examples to be named here include the development of drought resistant crops, the building on increased storage based on expected changes in water availability and the incidents of droughts or the increase in the heights of dikes based on expectations of an increase in the frequency of extreme flood events. Such strategies pose unrealistic expectations on the accuracy of climate change scenarios that can be derived from regional climate change models.

In parallel one could observe in scientific and policy communities an increase in the attention to adaptive management and robust measures. This is reflected in the guidance document on climate change and the implementation of the European Water Framework Directive (EC 2009) which states for example: Given deep uncertainty about regional climate change projections and realised impacts on aquatic ecosystems, RBMP should incorporate management strategies that deliver benefits regardless of the climate outlook. Robust and adaptive RBM measures are low regret, or reversible, incorporate safety margins, employ ‘soft’ solutions, are flexible, and mindful of the actions being taken by others to either mitigate or adapt to climate change.

This constitutes a fundamental shift compared with previous practice and guidance on the WFD implementation where uncertainty was either ignored or treated in a quite unsystematic fashion (Sigel *et al*, 2010). A robust measure can be defined as a measure which performs well under different yet uncertain future conditions which is a clear deviation from prevailing strategies towards optimization.

However, current management and governance practice is yet far from being in a position to implement such approaches in practice. Structural barriers include long-lived infrastructure and the prevailing of large infrastructure as prevailing design. Governance challenges abound. Sectoral fragmentation hinders integrated planning. Implementing innovative and integrated approaches in flood management and the design of resilient landscapes for example require coordination between flood management, water resources management, regional planning and agricultural policy.

A comprehensive comparative analysis of water basins in different countries all over the world showed that performance regarding climate change adaptation is supported by polycentric governance systems defined as having a distribution of power but effective coordination structures and innovative ways for dealing with uncertainty.

Major emphasis needs to be given to governance reform to build the capacity for climate change adaptation and design and implementation of resilient system that can deal with uncertainty and surprise.

3.6.2. Economics Costs of Impacts and Adaptation

In this section, we provide a summary of economic cost of climate change impacts and adaptation to global water resources infrastructure and systems. The impacts on economic sectors that use water resources is discussed in Chapter 10 and detailed regional and local impacts are reported in their respective chapters. We first summarize a number of studies which have estimated the possible impacts of climate change on the water sector in economic terms, and then review studies which have specifically examined the costs of adaptation.

3.6.2.1. Costs of Climate Change Impacts

Efforts to quantify the economic impacts of future climate-related changes in water resources are hampered by a lack of data, the uncertainties described in Section 2.3, and by the fact that the estimates are highly sensitive to both the cost estimation methods and the different assumptions used with regards to the allocation of changes in water availability across various types of water use (e.g., Chagnon, 2005; Schlenker et al., 2005; Young, 2005). In some regions hydrological changes may have impacts that are positive in some aspects and negative in others, for example increased annual runoff may produce benefits for a variety of both in-stream and out-of-stream water users by increasing renewable water resources, but may simultaneously increase flood risk. Overall, the IPCC states that it is very likely that the costs of climate change to the water sector will outweigh the benefits globally (Bates et al., 2008).

An early global study by Fankhauser (1995) estimated the regional impacts of a temperature increase of 2.5°C in various sectors, converted these to dollars, and then summed them to the global level. For the global water sector this yielded an estimated loss of ca. $47 billion. Tol (2002a) derived benchmark estimates of the costs of climate change in several sectors based on a review of climate change literature. For the water resources sector, this led to a loss of ca. $84 billion for the world as a whole for a global temperature increase of 1.0°C. In an accompanying study, Tol (2002b) developed a model of climate change impacts that accounts for the dynamics of climate change and the systems affected by it. For the water resources sector, many simplifying assumptions were made to develop a simple ad hoc model of the impacts of climate change on water resources. This model shows a loss to world GDP ranging from 0.5 to 1.5% by 2200 (Tol et al., 2002b). Tol et al. (2000b) clearly acknowledge and highlight the caveats of these studies, stating that the results are indications of potential pressure points and relative vulnerabilities, and are not useful as predictors or as input to decision analyses.

3.6.2.2. Costs of Adaptation to Climate Change

Considering the importance of adapting to climate change in the water sector, the literature on this topic is limited (EEA, 2007; Kuik et al., 2008). Estimates of the costs of adaptation to climate change across sectors at the global scale were not available until 2006. Since then, five multi-sectoral estimates of these costs have become available (Oxfam, 2007; Stern, 2006; UNDP, 2007; UNFCCC, 2007; World Bank, 2006b). These studies are discussed elsewhere in the EACC project, and hence are not discussed further in this working report.

At the local, national, and river basin level, the geographical distribution of these research is skewed towards developed countries, although examples do exist in developing countries. A regional study of the effects of climate change on water supply is available for sub-Saharan Africa (Muller, 2007). This research estimated the costs of adapting urban water infrastructure in sub-Saharan Africa to climate change to be USD 2 - 5 billion per year. This study assumes that: (a) reliable yields from dams will reduce at the same rate as stream flow (e.g., a 30% reduction in stream flow will mean a 30% reduction in reliable yield, and the unit cost of water will go up by more than 40%); (b) where waste is disposed into streams, a reduction in stream flow by x% will mean that the pollutant load must be reduced by x%; and (c) power generation reduces linearly with stream flow. The costs of adapting existing urban water storage facilities are estimated at $0.05 - 0.15 billion/year, and the costs of additional new developments are estimated at $0.015 - $0.05 billion/year. For wastewater treatment, the adaptation costs of existing facilities are estimated at $0.1 - 0.2 billion/year, and the costs of additional new facilities are estimated at $0.075 - $0.2 billion/year.

Assessment of the costs of adaptation in water resources at the global level Kirshen (2007) UNFCC, (2007) and Ward, et al 2010. These studies estimated the global costs of adaptation associated with additional water infrastructure needed. Kirshen reports that by 2030 to provide a sufficient water supply, given present and future projected water demands and supplies in more than 200 countries the adaptation costs will amount to ca. USD 531 billion in total for the period up to 2030. Of this, USD 451 billion (85%) is estimated to be required in developing countries, mainly Asia and Africa. The assessment of Kirshen (2007) was subsequently modified in UNFCCC (2007). In this study, two further costs were included, namely the increased cost of reservoir construction since the best locations have already been taken, and unmet irrigation demands. This report suggests that the total costs of adaptation will be ca. USD 898 billion for the period up to 2030. It is assumed that 25% of these costs are specifically related to climate change, and hence the cost of adaptation to climate change in the water supply sector is estimated at ca. USD 225 billion up to 2030. This is equivalent to ca. USD 11 billion/year (UNFCCC, 2007). Ward et al 2010 estimate the adaptation costs to provide enough raw water to meet future global industrial and municipal water demand, based on country-level demand projections to 2050 through a combination of increased reservoir yield and alternative backstop measures are estimated to be US$12B/yr., with 83-90% in developing countries.

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) and Connell-Buck *et al*. (2011) 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; 2009a) and Lopez *et al*. (2009) 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) and the adoption of 'resilient' approaches (Henriques & Spraggs, 2011). Adaptive water management techniques include scenario planning, employing experimental approaches which involve learning from experience, and the development of flexible solutions that are resilient to uncertainty. These solutions are not 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 no-regrets 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 can be seen as being 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). Other frameworks that have been proposed based on risk assessment include the threshold-scenario risk assessment framework (Freas *et al*., 2008), which combines a qualitative threshold risk assessment approach with quantitative scenario-based risk assessment.

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 and 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 tend 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. There is evidence that a number of agencies are beginning to factor climate change into processes and decisions (Kranz *et al*., 2010; Krysanova *et al*., 2010), with the amount of progress strongly influenced by institutional characteristics. This activity largely takes the form of the development of methodologies to be used in practice by water resources and flood managers. Much of this activity is reported in the professional 'grey' literature (e.g. Brekke *et al*, 2009a, describing proposed changes to practices in the United States), but some is described in the refereed literature (e.g. Arnell (2011) describing the evolution of methodologies for water resources assessment under climate change in England and Wales). Cullis *et al*. (2011) illustrate how climate scenarios could feasibly be incorporated into resource planning in practice, based on involvement of stakeholders in water resources planning in Polokwane, South Africa.

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 3-4.

[INSERT TABLE 3-4 HERE
Table 3-4: 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, and a major component of the approaches to water management in the face of climate change (Section 3.6.3) is their treatment of uncertainty. Some approaches use a small number of scenarios to represent the range in possible impacts. The approach used in England and Wales for the development of water resources adaptation responses, for example, uses a central estimate of the effects of climate change on reliable yields as a starting point for analysis, and characterises the effect of uncertainty through considering how options perform under a 'wet' and a 'dry' scenario (Arnell, 2011). Under such approaches, no attempt is made to assign likelihoods to the different scenarios considered.

Since the AR4, much attention has been directed towards methods which use very large numbers of scenarios to produce "likelihood distributions" of indicators of impact (*e.g.*, Lopez *et al*., 2009; Christierson *et al*., 2012) for use in risk assessment. 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 (*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.

Addressing the effects of uncertainty through its quantification in some form of risk assessment, however, is only one way of dealing with uncertainty. An alternative approach starts from the perspective of the characteristics of different adaptation options, and seeks to develop a strategy which is robust and resilient to uncertainty (*cross reference to other WG2 chapters which expand on these terms*). An example of this approach is provided by Henriques & Spraggs (2011), who considered different responses to future flood risk to critical water supply infrastructure. They used models and scenarios to identify potential risks and their uncertainties, and developed a strategy which enhanced both asset and system resilience. This combined low-regret options to protect individual sites from flooding with longer-term strategies to increase the robustness of the supply network to a wide range of potential disruptions.

Robust decision-making (Lempert *et al*., 1996; 2006) is a more formalised way of constructing robust and resilient adaptation strategies, and 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 and 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.

3.6.6. Capacity Building

Water resources management and development include 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. The idea of water development and management in IWRM is based on a participatory approach, involving users, planners and policymakers at all levels, where women play a central part in the provision, management and safeguarding of water. Water is seen as having an economic value in all its competing uses and might be recognized as an economic good. Institutional and local capacities are prerequisites for facilitating adaptation to climate change and are generally promoting best management practices, providing education, and raising awareness. Hence, strengthening the 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 e.g. community-based, participatory processes and traditional knowledge, and to acquire financial commitments for adaptation programs. Thus, in implementing successful adaptation measures, local people can be properly trained e.g. 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 might 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”, scientific research results can be analyzed preceding 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, might 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.

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 (Ivey *et al*., 2004; Naess *et al*., 2005; Crabbe and Robin, 2006)" (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; Falloon and Betts, 2010).

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. Water demand management has a significant impact on energy consumption as energy is required to pump and treat water, to heat it, and to treat waste water. Rough estimates for the USA result in a water-related energy consumption that is equivalent to 13% of the total electricity production, with 70% due to water heating and 14% due to waste water treatment (Griffiths-Sattenspiel and Wilson, 2009). Even though 34% of water withdrawals in the USA are for irrigation, only 5% of the water-related energy consumption occurs in the agricultural sector, mainly for groundwater pumping. For China, where agriculture is responsible for 62% of water withdrawals, groundwater pumping for irrigation accounts for only 0.5% of China's GHG emissions, a small fraction of the 17-20% share of agriculture as a whole (Wang *et al*., 2012).

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. and 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 and availability of data records are unevenly distributed geographically, and information on other relevant variables, such as soil moisture, snow depth and water equivalent, evapotranspiration, groundwater depth, and water quality including sediments, is mostly limited in developing countries. Relevant socio-economic data, such as rates of surface water withdrawal and exploitation of ground water by each sector, and information on already-implemented autonomous adaptations for securing stable water supply, are limited even in developed countries. In consequence, assessment capability is limited in general, and especially so in developing countries. There is very little peer-reviewed literature bearing on human-induced climate change as it affects the 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 in regional decision-making that aims for the best mix of mitigation and adaptation. Regional damage curves need to be developed, relating the magnitudes of major causes of water-related disasters (such as intense precipitation, surface soil dryness, and storm surges) to the expected costs.

There is a continuing mismatch between the large (~200-km) scale of climate models and the ~20-km catchment scale at which water is managed and adaptations must be implemented. Increasing the spatial resolution of regional climate models, or improving the accuracy of methods for downscaling their outputs, can produce information of more relevance to water management. Climatic extremes of concern in water management generally recur more frequently than the typical engineering criterion of a 1% probability of annual exceedance. Computing capacity will be required to address these problems with more ensemble simulations at high spatial resolution.

Interactions among socio-ecological systems are not yet well considered in assessments of the impact of climate change. Particularly, there are few studies on the impacts of mitigation and adaptation measures taken in other sectors on the water sector, and conversely. A valuable advance would be to couple hydrological models, or even the land-surface components of climate models, to data on water-management activities such as reservoir operations, irrigation and urban withdrawals from surface water or groundwater, based on the synthesis of case studies and research achievements from field surveys.

_____ START BOX 3-2 HERE _____

Box 3-2. Case Study: Himalayan Glaciers

As Himalayan glaciers retreat and shrink, they become foci of growing concern because they are important resources of freshwater for the five countries – Bhutan, China, India, Nepal and Pakistan – on whose territories they lie, and for Bangladesh. They are also significant globally, accounting for 6–7% of the extent of glacier ice outside the ice sheets. But it is hard to assess their evolution because measurements of change are very limited. Even the total amount of ice is known only roughly. 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). This estimate is uncertain by some tens of percent. Taking into account the dependence of glacier thickness on slope, the total mass could be as small as 2300 Gt (Bolch *et al.*, 2012).

Observations

Observed reductions of glacier length in the Himalaya vary greatly, but it is difficult to ascribe these reductions to climatic forcing even when multiple measurements are averaged. For example debris-covered glacier tongues are common; they tend to be stagnant and to have stable termini, which therefore convey little or no information about climate (Scherler *et al.*, 2011).

Figure 3-10a summarizes all published regional-scale measurements of reduction of glacier area. There is no clear pattern, 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 most frequently measured rates are near –0.10% a^{-1}, but the distribution is skewed towards faster rates of loss.

[INSERT FIGURE 3-10 HERE

Figure 3-10: a) Published sub-regional shrinkage rates from the Himalaya. b) Measured mass-balance rates from the Himalaya (Bolch *et al.*, 2012). 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).]

The most informative measure of glacier change is the mass budget. Himalayan mass budgets, 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.

More information is now available on the Karakoram anomaly, an apparent slowdown of mass loss in the central, highest parts of the Karakoram that was first inferred from circumstantial evidence. The first direct measurement of mass balance in the Karakoram, for 1999–2008 and covering 5615 km^2, was indeed slightly positive (Gardelle *et al.*, 2012).

Projections

If the average rate of mass loss during 1975–2008 is sustained, the mass of glacier ice in the Himalaya in 2035 is projected to be 38–62% of its mass in 1985 (Cogley, 2011). However, if the rate were to continue to accelerate as observed during 1985–2008, the percentage remaining in 2035 would be 18–42%. Confidence in these projections is *low* because of the observational shortcomings mentioned above and because the method of simulation was very simple. The simulated mass losses depend on rates of area loss that are simulated as being greater than those found in the limited measurements. Thus the estimated mass losses may be exaggerated, but better estimates must await better information and more detailed modeling.

Some hydrological simulations agree satisfactorily with observations in Himalayan catchments (e.g., Rathore *et al.*, 2009), but 21st-century projections do not yet present a coherent region-wide picture. Two models each showed the expected shift of seasonal maximum discharge from summer towards spring in a simulation of the discharge of three rivers in northern Pakistan for 2071–2100, but they agreed poorly on magnitudes of discharge decrease (Akhtar *et al.*, 2008). The increment of glacier meltwater production under the SRES A1B scenario was found to be of the order of +100 mm a^{-1} by 2025–2030, but this was a highly generalized analysis (Ren *et al.*, 2007).
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. For an imposed warming rate of 0.06 K a^{-1}, simulated peak meltwater discharge was reached in hypothetical glacierized basins around 2050 in the drier western Himalaya and around 2070 in the wetter eastern Himalaya (Rees and Collins, 2006).

Impacts

No study has yet offered a firm statistical attribution of Himalayan glacier changes to human activities. However, the growing atmospheric burdens of dust (Das *et al.*, 2010) and soot (Xu B.Q. *et al.*, 2010), largely of human origin, have received increased attention. Measurements of atmospheric black carbon 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 meltwater. Energy-balance calculations (e.g. by Qian *et al.*, 2011) show that deposited soot is likely to outweigh the greenhouse effect as a radiative forcing agent for snowmelt. Time series of soot in several ice cores from the Himalaya-Tibetan region are irregular (Xu B.Q. *et al.*, 2010), and a recent increase in soot in an ice core from Mt. Everest is not well matched with increases in south Asian emissions (Kaspari *et al.*, 2011). These observations suggest that soot has reached Himalayan snowpacks from both nearby and distant sources in recent decades.

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

Himalayan glacier meltwater 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, but the relative contribution of the glaciers to water resources decreases with distance downstream. At regional scales, the contributions are relatively greatest where rivers such as the Indus enter seasonally arid regions, and may become negligible in the downstream parts of monsoon-region basins such as the Ganges–Brahmaputra (Kaser *et al.*, 2011). In the mountains, however, both dependence on and vulnerability to glacier meltwater can be of serious practical concern when measured per head of population.

_____ END BOX 3-2 HERE _____

Frequently Asked Questions

FAQ 3.1: How will the availability of water resources be affected by climate change?

Climate models project both increases and decreases of available water at the regional scale. Evapotranspiration will increase, and average annual runoff is generally projected to increase at high latitudes and in the wet tropics and to decrease in most dry tropical regions. Reliable surface water supply is likely to decrease in many regions because of decreases in snow/ice storage and groundwater recharge, degradation of water quality, and more variable streamflow due to more variable precipitation. Floods and droughts will become more frequent.

FAQ 3.2: How will floods and flood damages develop due to climate change?

Floods are natural phenomena defined as a water level, above the average flow, that produce overflowing of land that is not usually submerged. Source of floods are intense rainfall, snow & ice-melt, combined rain & ice-melt, and breakdown of natural dams (e.g. iced-dam lakes in glacial retreat regions). Flood hazards refer to the occurrence of a flood of a given magnitude, and there are commonly defined in statistical terms, based on the analysis of a sample based on previous recorded events. As floods are rare hydrological events (frequency <1 flood in 10 years), the number of events from historical records is limited and their trends are difficult to establish. Thus, there is a low confidence due on the short available records that climate change has affected the magnitude or frequency of floods worldwide, although in some regions changes on precipitation intensity and snowmelt patterns have an effect on flooding (medium to high confidence). Floods may have adverse effects on exposed and vulnerable elements (a predisposition to loss and damage) that entail social, economic, or environmental impacts, becoming a “natural disasters”. There is a medium to high confidence that flood damages have increased worldwide, mainly determined by increased exposure of people and economic assets (high confidence), although the role of climate change enhancing floods has not been excluded (high agreement, medium evidence). However, flood damages (disasters) may be triggered by events that are not extreme in a statistical sense but depends on social conditions that increase exposure and vulnerability. Therefore, the increased flood damages are not necessarily related to an increased frequency or magnitudes of flooding.

Simulation of reliable extreme hydrometeorological conditions conducive to flooding is a complex task, in most cases with a high uncertainty. There is a low confidence in projected changes in flood magnitude and frequency, although projected increase in heavy precipitation and earlier spring peak floods are very likely to occur at some regions, thus increasing flood risks. There is a high agreement that future flood losses in many locations will increase in the absence of additional protection measures, but the estimated change is highly variable depending on location, climate scenario used, and methods used to assess exposure and vulnerability.

FAQ 3.3: Are climatic changes more serious than other human impacts on freshwater?

In general, climatic changes are considered to put additional stress on freshwater systems, many of which are already affected by other human stressors. These stressors include land use change, water withdrawal, artificial drainage of wetlands, dam construction, alteration of river morphology, and water pollution. The impact of climatic changes on freshwater has a different character than the impact of other stressors. Unlike other stressors, climatic changes lead to impacts on freshwater systems all over the globe. Furthermore, they lead to changes in the volume and intensity of precipitation, i.e. changes of the source of all water on the continents. Thus, they affect all compartments of the freshwater system (soil, groundwater, lakes, wetlands etc.). Whether the stress caused by climatic changes is more serious than other anthropogenic stresses certainly depends on the considered region and freshwater compartment or type of stress. Considering the increased risk of flooding in most areas of the globe due to increased occurrence of heavy rainfall, for example, there is no other human stress that could cause such an impact. Considering streamflow reductions, however, irrigated agriculture has already led, in some semi-arid regions, to impacts that are comparable or worse than those expected from climatic changes. Finally, the answer to the question depends on the time horizon and on the success of climate change mitigation efforts. As global population is expected to reach its maximum at the middle of the 21st century, while climatic changes may not peak until much later (depending on our greenhouse gas emissions), climate change impacts will become comparatively more serious over time as compared to other human impacts.

FAQ 3.4: How should water management be adapted in the face of climate change?

Water resource adaptation options need to be able to function under uncertain future climate change, but many adaptation measures do not sufficiently account for this. The building of dams and large-scale irrigation systems for example cannot completely protect against floods and can also damage the adaptation capacity of other sectors, an example of maladaptation. Technical measures such as desalination, pumping of deep groundwater, and water treatment are very resource intensive. Increasingly it is becoming recognized that water management requires an integrated approach, through “integrated watershed management” which includes natural resource management along with social measures and infrastructure development. In principle, restoring and protecting freshwater habitats and watersheds and managing natural floodplains are a key element of such an approach.

Particulary in developing countries, adaptation options include;expanded rainwater harvesting; water storage and conservation techniques; water re-use; desalination; water-use and irrigation efficiency, such as improved soil and water management, maintaining vegetation cover, planting trees on slope fields, mini-terracing for soil and moisture conservation, improved pasture management, conservation tillage and rain water harvesting.

FAQ 3.5: Does climate change imply only bad news about water resources?

In a warmer climate the balance between precipitation and evaporation will shift. There will be more of both but not, in general, in the same places. Regions with abundant water at present will have yet more, and regions with deficits will suffer more serious shortages. These changes are already well attested globally, but at the regional scale they are subtle and in most regions it will be some decades before they become detectable in the statistical sense.In regions where water shortages are made good by glacier meltwater there will be a “meltwater dividend” during the 21st century, but the total yield of meltwater will eventually diminish. Many of the regions that are adversely affected by changes in water resources are in the developing world, where water resource management can be traditional (in the technical sense) or ineffective. Regions where water resources are heavily managed might experience a more positive effects, including improvement in seasonal availability of water, under climate change.

FAQ 3.6: How are portfolio and no-regrets adaptation measures defined?

A portfolio of adaptation measures is a set of options, defined at a local level, that are considered to address the variable conditions of future climate scenarios. They are measures that can be progressively implemented in a coordinated and complementary way in order to adapt in a flexible manner to the different and variable future conditions. The selected measures are intended to reduce vulnerability and increase resilience. As part of the portfolio of measures, those that are considered as “no-regrets” options are to be used as much as possible. No-regrets options are those that will yield benefits regardless of whether or if, the climate changes. For instance providing universal access to safe water is a no-regrets option.

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Table 3-1: Observation, detection and attribution of impacts of climate change on freshwater resources (sources correspond to those in Figure 3-2).

Observed change	*Attributed to*	*Source*
More intense extremes of precipitation (northern tropics and mid-latitudes, 1951–1999)	Anthropogenic greenhouse-gas emissions	1
Fraction of risk of flooding (England and Wales, 2000)	Extreme precipitation due to anthropogenic greenhouse-gas emissions	2
Decreased recharge of karst aquifers (Spain, 20th century)	Decreased precipitation, increased temperature	3
Decreased groundwater recharge (Kashmir, 1985–2005)	Decreased winter precipitation	4
Increased faecal pollution in surface water (California, 1969–2000)	Increased storm runoff due to increased precipitation	5
Reduced water quality (River Meuse, western Europe, 1973–2003)	Droughts, increased air and water temperature	6
Increased lake nutrient content (Victoria, Australia, 1984–2000)	Increased air and water temperature	7
Nutrient flushing from swamps, reservoirs (North Carolina, 1970s–2002)	Hurricanes	8
Lake warming at 0.13 ^{o}C/yr (Nevada, 1970–2007)	Increased air temperature	9
Increased inflow of dissolved oxygen to a reservoir during ENSO episodes (Spain, 44 years of data)	Increased storm runoff due to increased precipitation	10
Increased dissolved organic carbon (DOC) concentrations (United Kingdom, 1995–2004)	Increased temperature and precipitation, and also acid deposition, land use, nitrogen and CO_2 enrichment	11
Temporal variations in nitrate fluxes (western France, 2–6 years)	Changes in precipitation and temperature, but also confounding anthropogenic factors	12

Table 3-2: Hydrological changes and freshwater-related impacts of climate change on humans and ecosystems that could be avoided with reduced greenhouse gas emissions.

Type of hydrological change or impact	Description of indicator	Hyd. change (or impact) in different emissions scenarios	Reference
Change of river discharge in six river basins around the world	Mean annual flows, statistical low flows and high flows	With GW increasing from 1°C to 6°C, the percent changes from historic conditions increase in almost all cases	Gosling et al. (2011)
River flow regime shift for river in Uganda	Shift from bimodal to unimodal (1 GCM)	Occurs in scenarios with GW of at least 4°C but not for smaller GW	Kingston and Taylor (2010)
River flow regime shifts from perennial to intermittent and vice versa, global scale	Area affected by regime shifts by the 2050s in percent of global land area except Greenland and Antarctica (0.5° grid cell resolution; range of 2 GCMs)	A2: 6.3-7.0 B2: 5.4-6.7	Döll and Müller Schmied (2012)
Decrease of groundwater recharge, global scale	Number of people affected by a groundwater recharge decrease of more than 30%, in % of world population around 2050 (range of 2 GCM)	A2: 6.2-6.4 B2: 4.3-4.5	Döll (2009)
Change of groundwater recharge in the whole Australian continent	Probability that groundwater recharge does not decrease to less than 50% of 20th century value by 2050), based on ensemble of 16 GCMs	GW 1.0°C: close to 1 almost everywhere GW 2.4°C: in western Australia 0.5-0.8, in central Australia around 0.8, elsewhere close to 1	Crosbie et al. (2012), their Fig. 4, submitted[1]
Change in groundwater recharge in East Anglia, UK	Percent change between baseline and future groundwater recharge, in %, by the 2050s (1 GCM)	A1f: -26 B1: -22	Holman et al. (2009)
Change of river discharge, groundwater recharge and hydraulic head in groundwater in two regions of Denmark		Changes for B2 often larger than for A2	Van Rossmalen et al. (2007)
Salinization of artificial coastal lake IJsselmeer in the Netherlands (a drinking water source)	1 Daily probability of exceedance of maximum allowable concentration (MAC) of chloride (150 mg/l) 2 Maximum duration of MAC exceedance (2050, 1 GCM)	GW 1°C, no change in atmosph. circulation: 3.1%, 124 days GW 2°C and change in atmosph. circulation: 14.3 %, 178 days Reference period: 2.5%, 103 days	Bonte and Zwolsman (2010)
Decrease of hydropower production at Lake Nasser, Egypt	Mean decrease of mean annual hydropower production by the 2050s, in % of current hydropower production (11 GCMs)	A2: 7 B1: 8	Beyene et al. (2010)
Flood damages in Europe (EU27)	1 Expected annual damages, in 2006- € 2 Expected annual population exposed (2080s, 2 GCMs)	A2: 18-21 billion €/yr , 510.000-590.000 people B2: 14-15 billion €/yr , 440.000-470.000 people Reference period: 6.4 billion €/yr, 200.000 people	Feyen et al. (2012)

GW: Global warming

Table 3-3: Climate change adaptation options regarding freshwater.

Objective	**Options**
Improve information	Improve information about quantity, quality and uses of water resources; vulnerability of populations, buildings and urban activities to natural disasters; and levels of contamination and how pollutants are exchanged between air, water and soil. Include how these factors vary with time, weather conditions and across different societal sectors.
Improve water management practices	Create institutions and enhance legislation and governmental tools which support integrated water management, allowing balanced interactions and input between all stakeholders, and considering economic and social aspects in order to provide a fair and equitable distribution of water. Identify "no-regret policies". Through these institutions promote growth of different sectors according to water availability; optimize activities across sectors; combine water and energy savings; integrally plan the management of land and water resources; share relevant information, including case studies, between sectors, users, federal, regional and local institutions; include ecosystems as important water users in legal and institutional frameworks; determine water requirements of ecosystems and provide specific allocations; create resilience by forming water utilities networks working teams; create water management portfolios that combine and integrate different policies, to add flexibility and support the sustainable use of water; design decision-making tools for use under uncertain conditions to fulfill multiple objectives from a public perspective; and take into account linkages between water quantity and quality. Use increase of water resources due to climate change to operate dams to the benefit of freshwater ecosystems. Develop financial tools (credits, subsidies and public investment) for the sustainable management of water.
Improved design and operation of water services	Extend the water services concept to cover: surface, groundwater and non conventional water sources management; water quantity and quality; flood prevention and control; sewers management; water, wastewater and reclamation treatment systems; a combination of hard infrastructure and soft adaptation options; storm water management; control of point and non-point pollution sources; basin drainage management; proper reintegration of used water to the environment; energy recovery from infrastructure; and sludge disposal and revalorization. Revise design criteria of water services to optimize flexibility, redundancy and robustness rather than cost, and repair and upgrade existing infrastructure to reflect changes in working conditions, i.e. variable quantity and quality of influent, impacts of floods or droughts. Ensure plans and services robust, adaptable or modular, good value, maintainable, and with long-term benefits, especially in developing countries. Develop infrastructure by combining green and gray infrastructure to manage wet weather sewerage flows; implementing treatment procedures for CSO (combined sewer overflows); improve infrastructure to cope with variations in influent quality and quality; and adopting and combining decentralized and centralized systems for supply and sanitation.
Reduce water demand and waste	Reduce demand through water and wastewater reuse within and between sectors; improved leak prevention; improved irrigation efficiency and re-leveled agricultural soil; public water saving programs; decoupling of a high quality of life with a high water and energy demand; tariffs (where there is elasticity); industrial certifications; economic and physical incentives; use restrictions in stressed areas; improved building codes; utilization of traditional farming techniques; improved reservoir management methodologies (to reduce evaporative losses); relocation of thirsty industries and crops to water rich areas; switch to more appropriate crops (drought resistant, low water demand, can be irrigated with wastewater); reduce consumption of meat produced by feeding with irrigated crops.
Increase water supply and reliability	Increase resilience to climate change by diversifying water sources (including rainwater capture where appropriate); repairing existing infrastructure; increasing storage capacity and water retention time; improved reservoir management methodologies to maximize yields from a given catchment and storage combination; and recharging aquifers as a way of storing water.
Prevent pollution and reduce its impact	Prevent pollution of water bodies through vegetative buffers to prevent surface runoff; physical barriers to prevent contamination of wells; aquifer recharge in coastal areas to prevent aquifer salinsation; responsible pesticide and fertilizer application (especially during wetter months); improved regulation and monitoring of industrial discharges, especially concerning toxic products that are recalcitrant to treatment processes; use of wetlands as wastewater treatment in agricultural areas; properly reintegrate wastewater into the environment (rather than thinking of it as a waste

	product that must be disposed of); control of erosion in agricultural areas; and providing universal sanitation, considering the whole chain for the service (including empting latrines and proper treatment and disposal of sullage and sludge). Reduce the impact of unavoidable contamination through diluting polluted water (e.g. with salts, fluorides, and arsenic) with non-polluted water; switch to crops resistant to salinity; promotion or provision of household treatment systems; and use of bank filtration to depollute water.
Reduce impact of natural disasters	Reduce the impact of natural disasters, such as floods and droughts, through early warning and monitoring systems; improved flood defenses or increased flood retention areas; contingency plans, use of flood or drought resistant crops; use of dams and reservoirs to help manage floods; promotion of water harvesting, and control of erosion and deforestation (to reduce runoff intensity); improved infiltration rates through permeable pavements, rain gardens, etc; improved collection of municipal solid wastes and control of dumping sites to avoid clogging of sewers; relocation and limitation of growth of industries and settlements in flood-prone areas; flood-proof storage of chemicals, fuel and equipment; improved defense and site selection for key infrastructure; recharge aquifer with excess water; implement actions to control the spread of diseases related to stagnant water; use of “floating crop beds” or hydroponics in frequently flooded land; creation of relief deep boreholes, with use restricted to drought periods; and creation of water storage and retention areas, such as stormwater ponds, canals, infiltration facilities, wetlands and green roofs.

With information from: Andrews (2009), Bahri (2009), de Graaf, Rutger and van der Brugge Rutge (2010), Dembo, (2010), Dillon and Jiménez (2008), Elliot et al., (2011, Emelko et al., (2011), Foster et al., (1998), Godfrey et al., (2010), Jimenez (2006, 2009, 2011), Jimenez and Asano (2008), Keller (2008), Marsalek et al., (2006), McCafferty (2008), Mayol (2008), McGuckin R. (2008), Mukhopadhyay and Dutta (2010), Munasinghe, (2010, NACWA, 2009, OECD (2010), OFWAT (2009), Rae Mackay (2010), Reiter (2009), Renofalt et al. 2010Seah (2008) , Sprenger et al. (2011, Thöle (2008), UNESCO (2011), UNHABITAT (2008) , Vörösmarty et al., (2000), Zwolsman et al., (2009).

Sullage (DEFINITION): Mixture of wastewater and sludge extracted from latrines

Table 3-4: 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

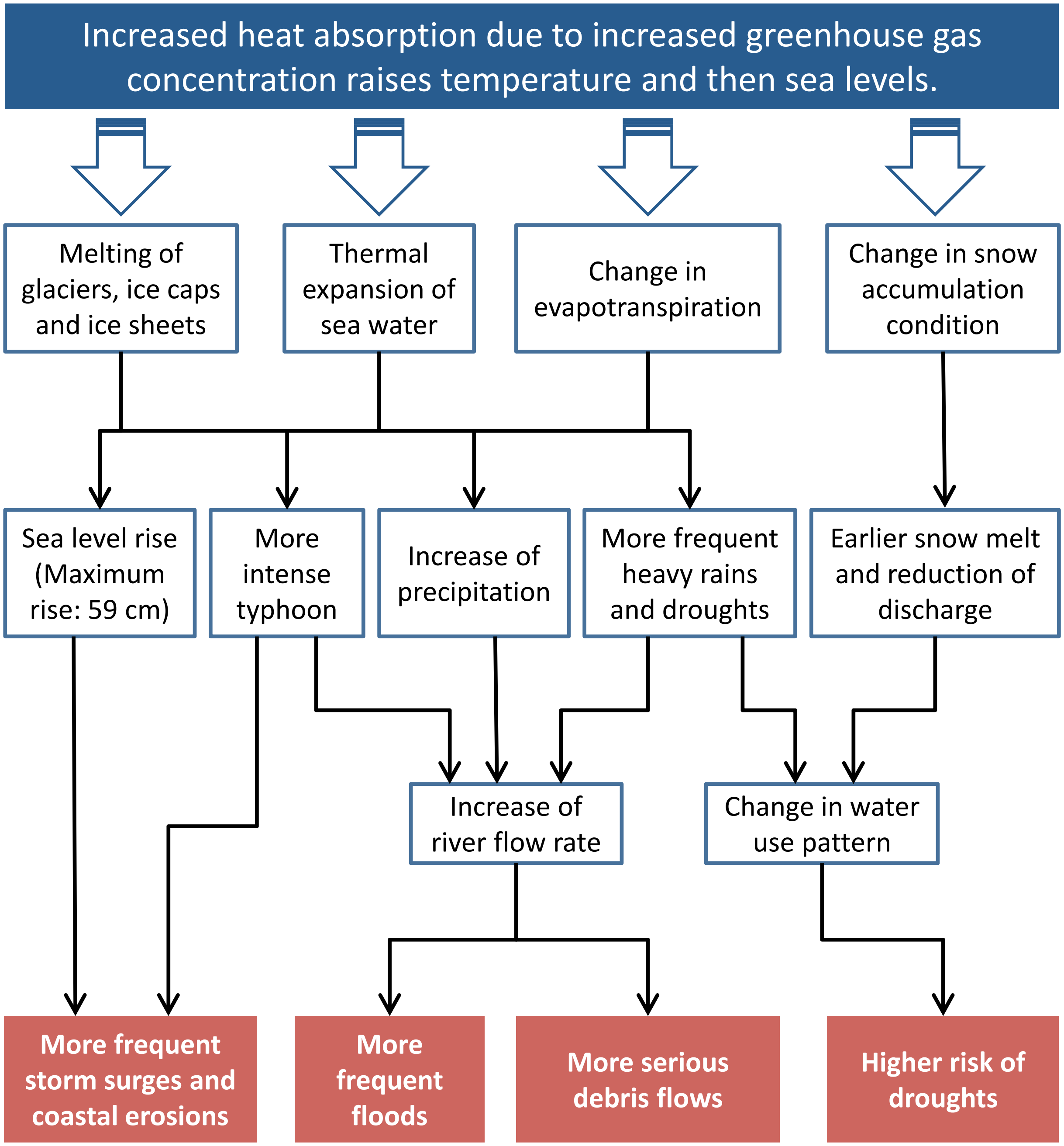

Figure 3-1: Framework considering the impacts of climate change on freshwater systems and society.

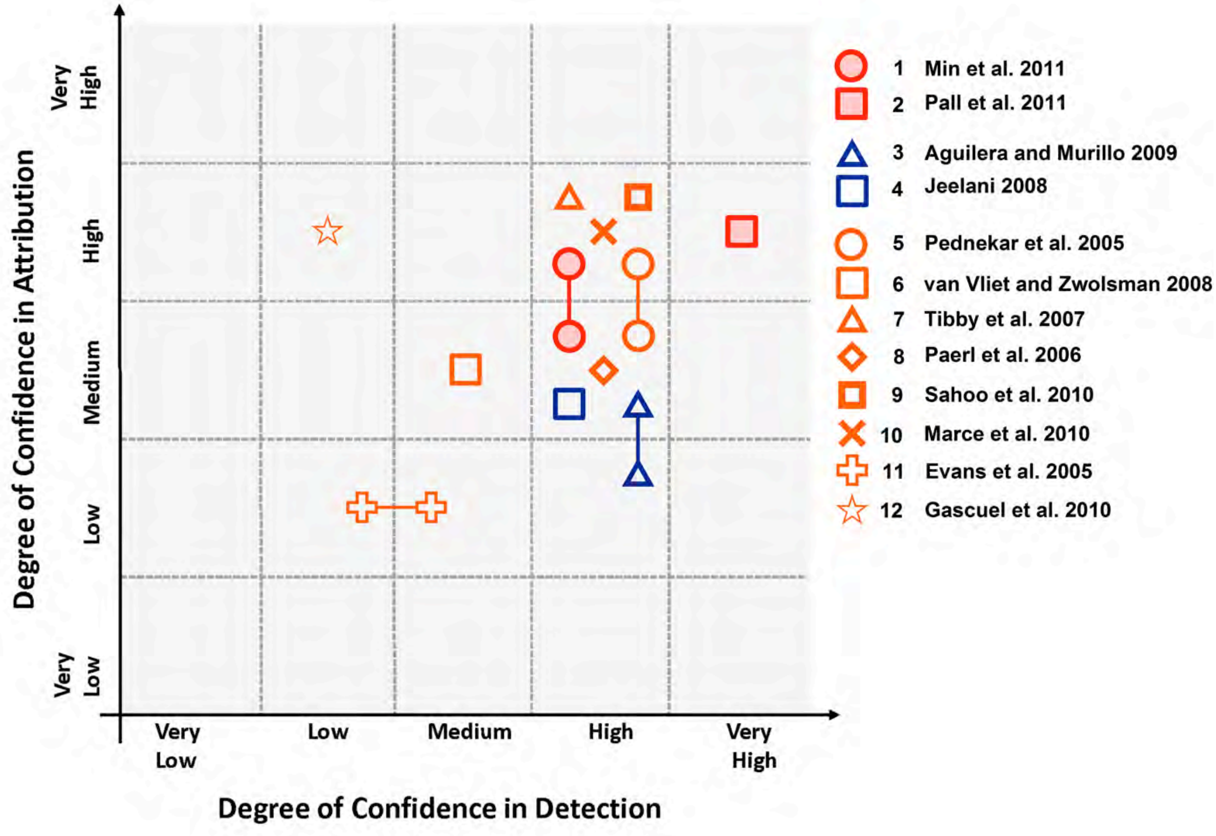

Figure 3-2: Confidence in detection and attribution of observed (not projected) impacts of climate change on freshwater resources; see Table 3-1 for further details. Different colours represent different subjects (red: extremes; blue: groundwater; orange: water quality). Filled symbols represent end-to-end attribution of hydrological change to anthropogenic climate change; open symbols represent attribution to climate change. The positions of symbols within grid cells have no quantitative significance.

Caveat: This is a placeholder. The list of studies shown is expected to change.

Caveat: identical symbols of different colours may cause difficulty for colour-blind readers; this will be worked on.

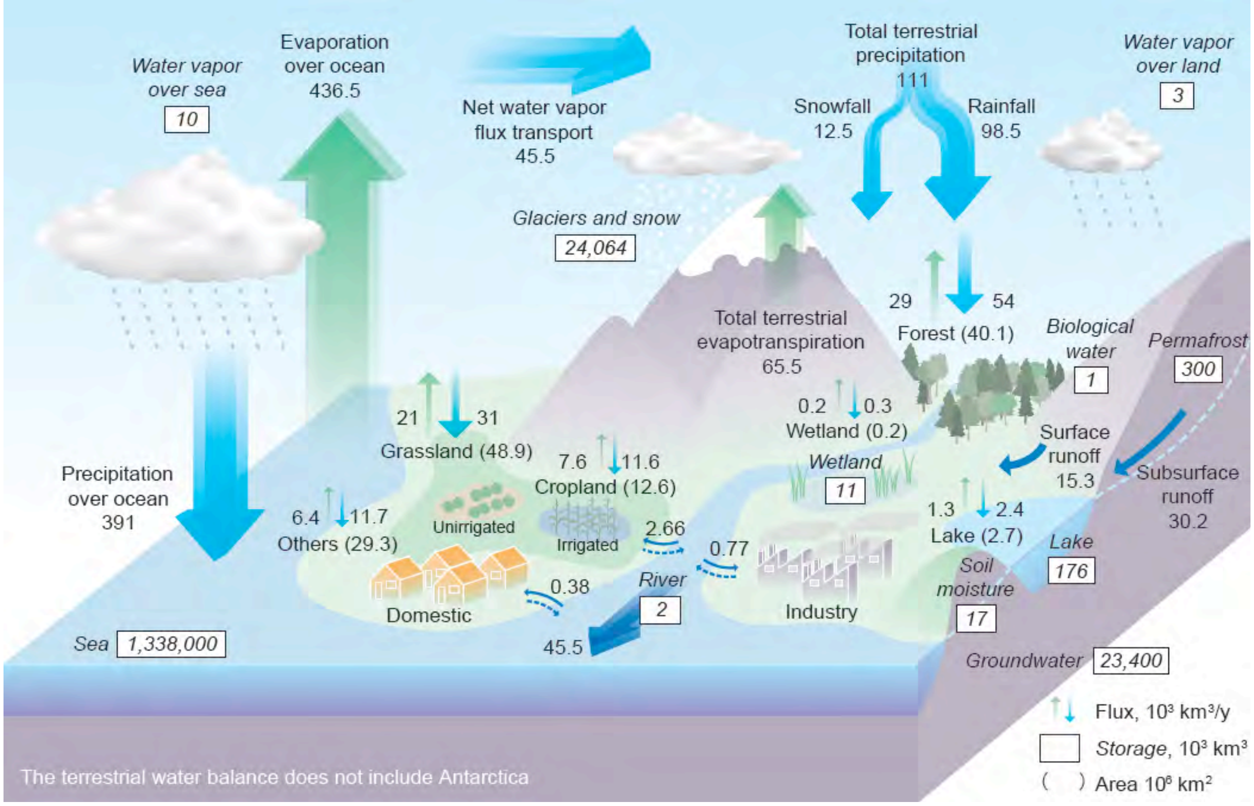

Figure 3-3: Global hydrological fluxes (1000 km^3/year) and storages (1000 km^3) with natural and anthropogenic cycles are synthesized from various sources. Big vertical arrows show total annual precipitation and evapotranspiration over land and ocean (1000 km^3/year), which include annual precipitation and evapotranspiration in major landscapes (1000 km^3/year) presented by small vertical arrows; parentheses indicate area (million km^2). The direct groundwater discharge to the ocean, which is estimated to be about 10% of total river discharge globally, is included in river discharge. (Oki and Kanae, 2006)

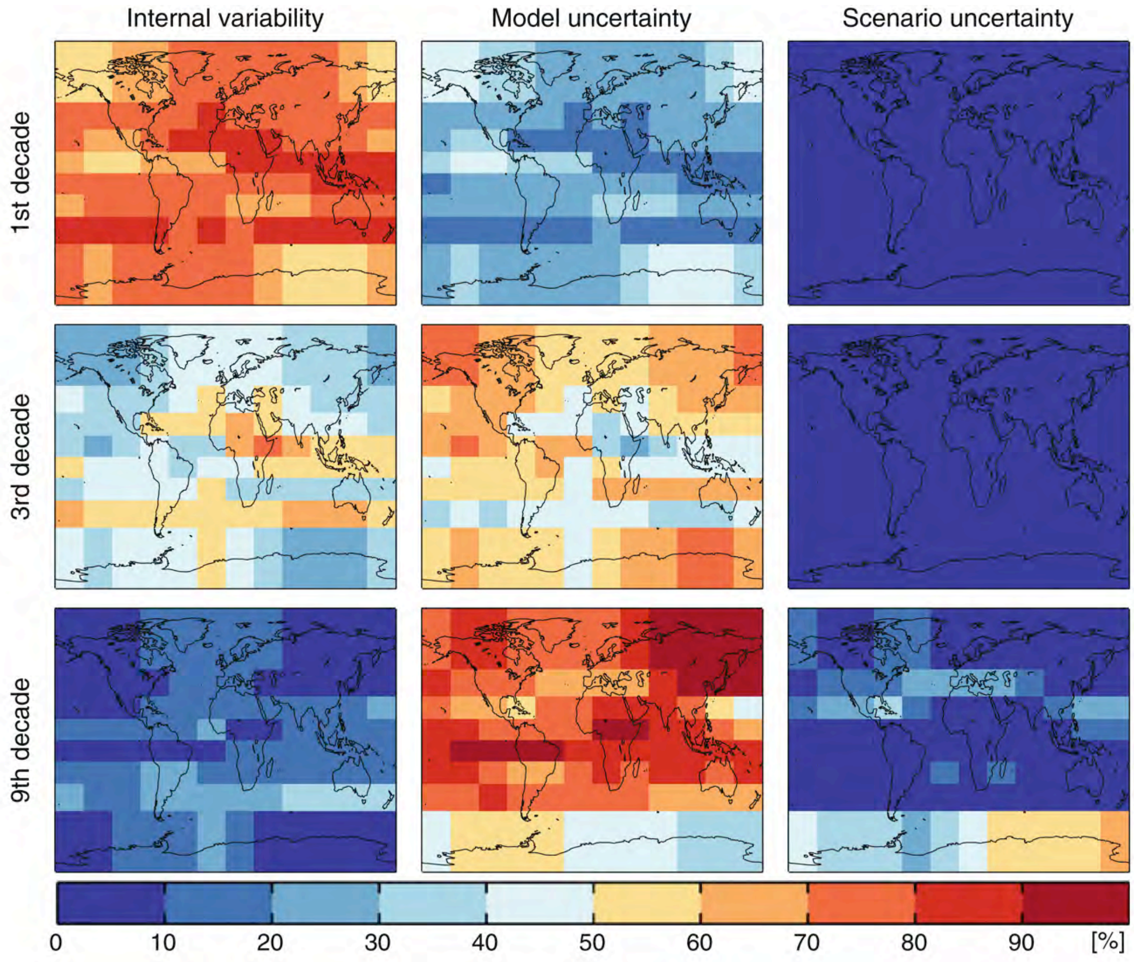

Figure 3-4: Fraction of variance in projections of changes in decadal-mean precipitation for boreal summer (JJA), decomposed into contributions from three sources of uncertainty. Simulations were for 2000–2100 under the SRES A1B, A2 and B1 scenarios, with a single ensemble member taken from each of 14 CMIP3 GCM experiments. From Hawkins and Sutton (2011).

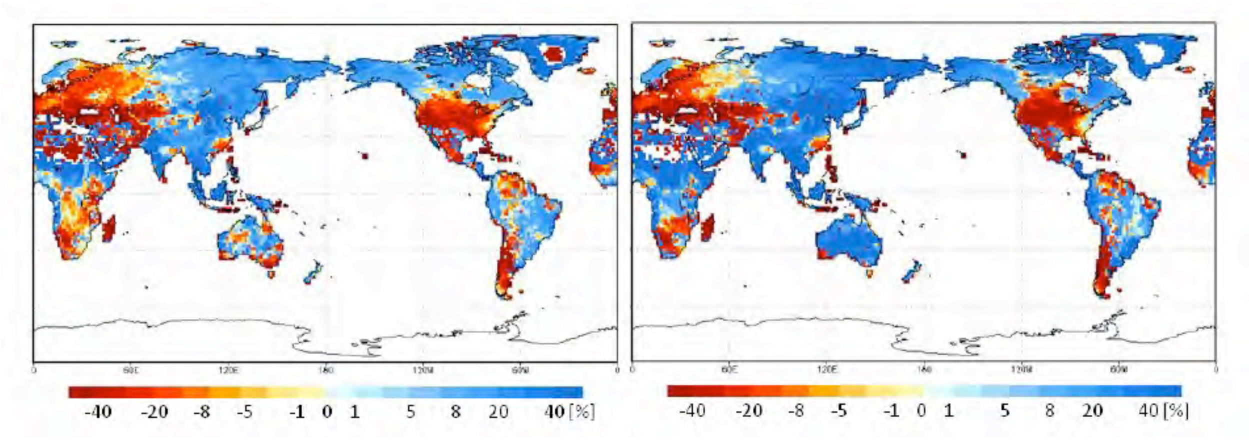

Figure 3-5: Map of percentage change of future river discharge (2080-99 average relative to 1980-99 average) simulated by MIROC5 under RCP 4.5 (left) and RCP 8.5 (right) scenarios. (Okazaki *et al*., 2012)
(They are the results of single GCM, and they will be replaced with those of multi-GCM.)

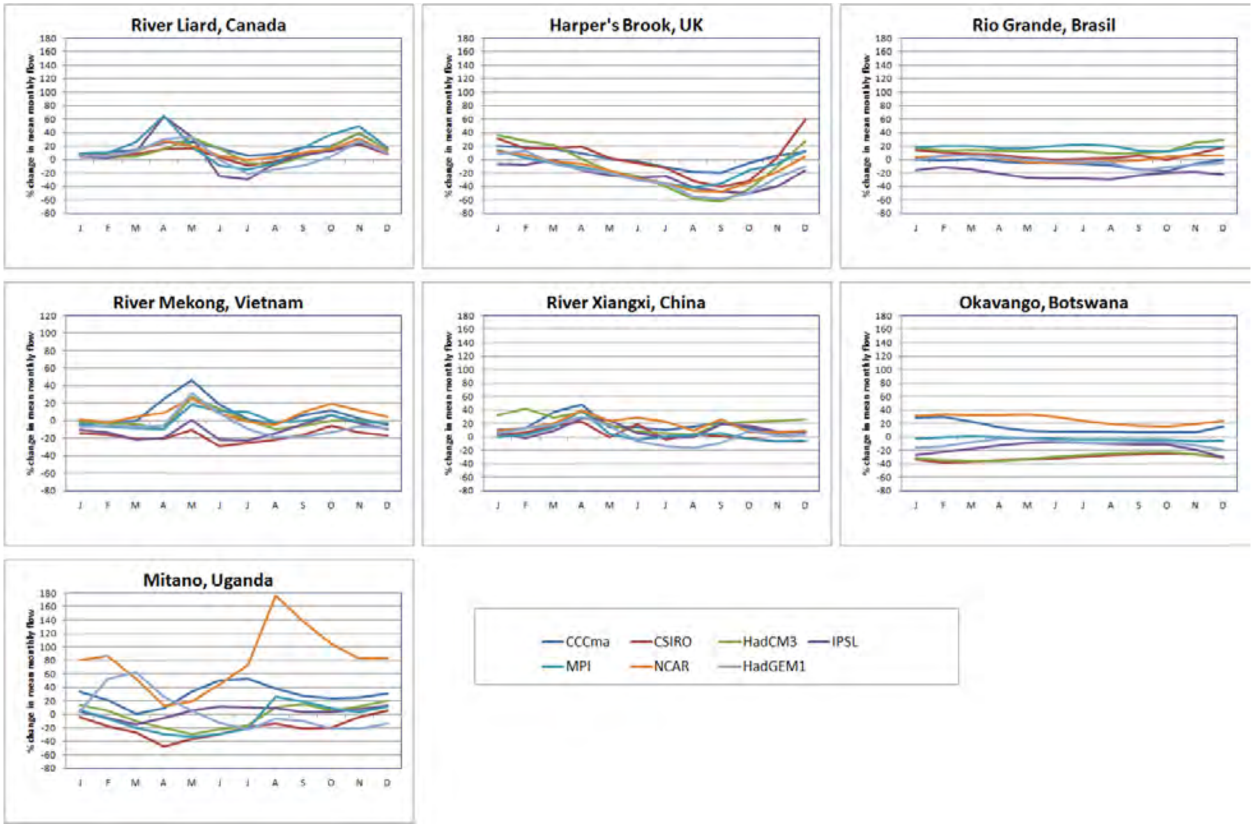

Figure 3-6: Change in mean monthly runoff in seven catchments, with a 2°C increase in global mean temperature (above 1961-1990) and seven climate models: (Hughes et al., 2011; Kingston and Taylor, 2010; Kingston et al., 2011; Nobrega, 2011; Thorne, 2011; Xu et al., 2011; Arnell, 2011b)

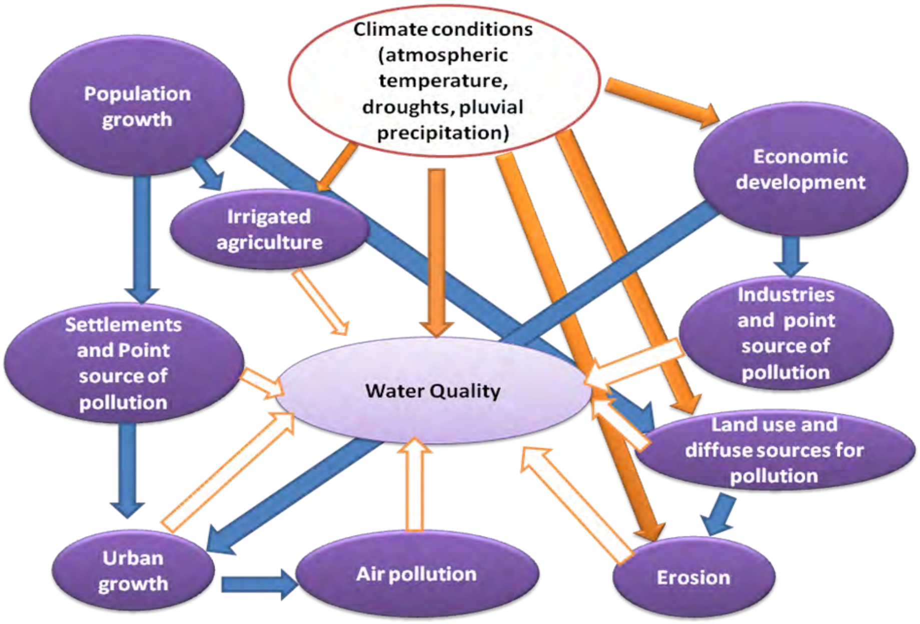

Figure 3-7: Complexity of the interactions on different factors impacting water quality.

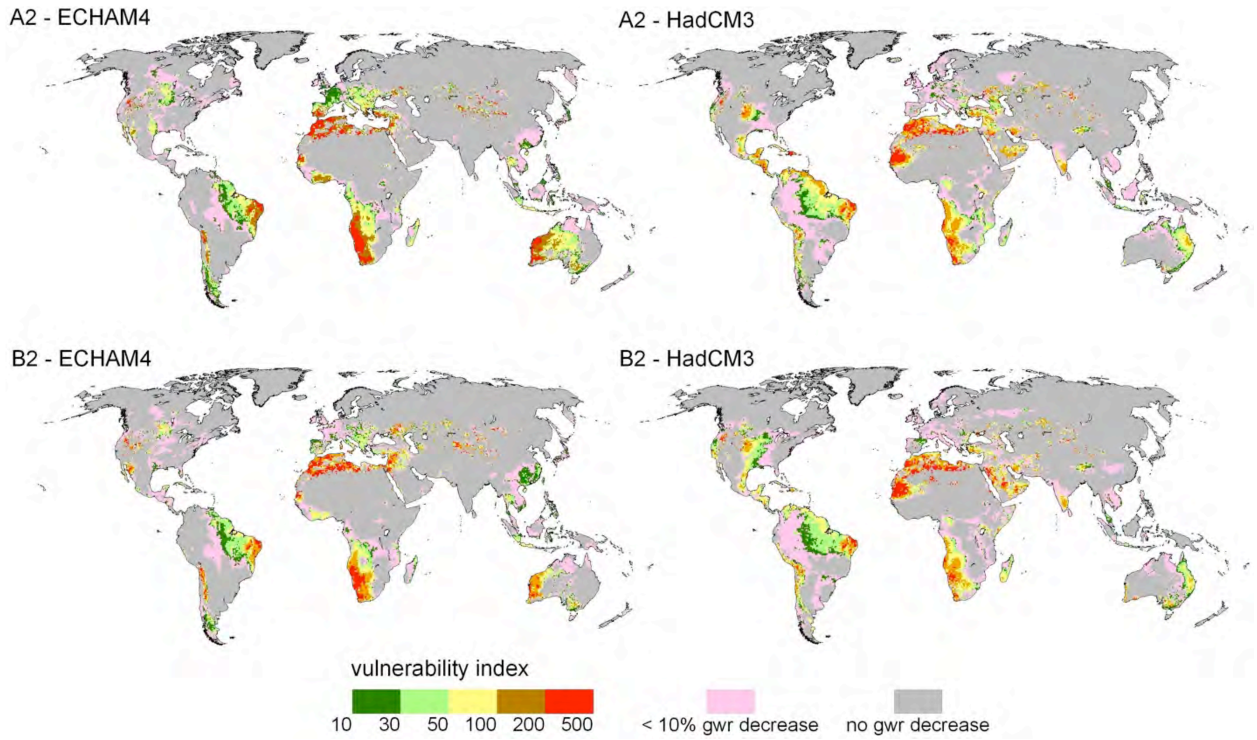

Figure 3-8: Human vulnerability to climate change induced decreases of renewable groundwater resources by the 2050s for four climate change scenarios. The higher the vulnerability index (computed by multiplying percent decrease of groundwater recharge by a sensitivity index), the higher is the vulnerability. 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).

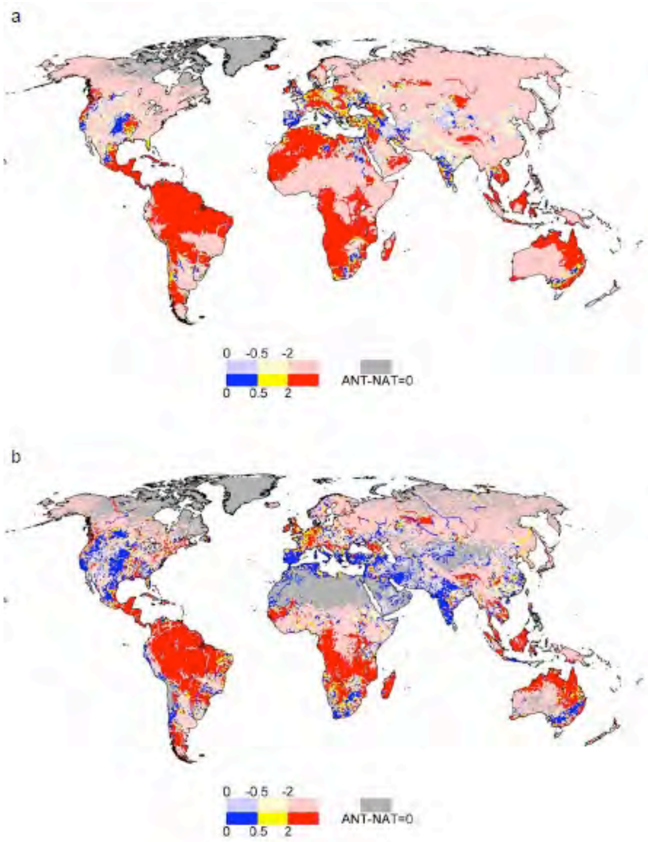

Figure 3-9: Ratio of the impact of future climate change to the impact of current dams and water withdrawals for long-term average annual discharge (a) and monthly low flow Q90 (b). Red colors indicate that the impact of climate change on the flow variable is at least twice as strong as the impact of dams and water withdrawals, blue colors the opposite. Intensive colors indicate that both drivers lead to the same direction of change of the flow variable, while soft colors the opposite. 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 (Döll and Zhang, 2010).

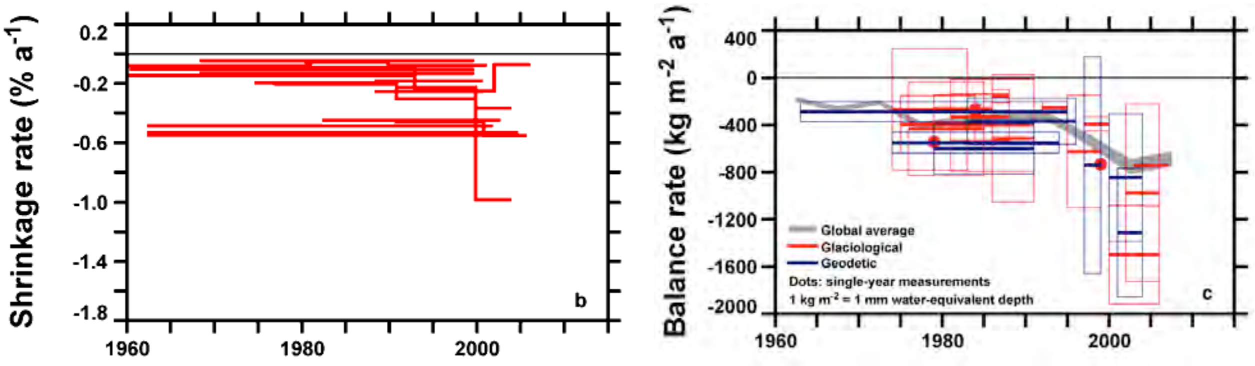

Figure 3-10: a) Published sub-regional shrinkage rates from the Himalaya. b) Measured mass-balance rates from the Himalaya (Bolch et al., 2012). Glaciological measurements are made annually in situ on the glacier. Geodetic measurements, mostly multi-annual, compare a later map to an earlier one. Each balance is drawn as a thick horizontal line contained in a ±1 standard deviation box (±1 standard error for geodetic measurements).