Chapter 3. Freshwater Resources

Coordinating Lead Authors
Blanca E. Jiménez Cisneros (Mexico), Taikan Oki (Japan)

Lead Authors
Nigel W. Arnell (UK), Gerardo Benito (Spain), J. Graham Cogley (Canada), Petra Döll (Germany), Tong Jiang (China), Shadrack S. Mwakalila (Tanzania)

Contributing Authors
Thomas Fischer (Germany), Dieter Gerten (Germany), Regine Hock (Canada), Shinjiro Kanae (Japan) , Xixi Lu (Singapore), Luis José Mata (Venezuela), Claudia Pahl-Wostl (Germany), Kenneth M. Strzepek (US), Buda Su (China), B. van den Hurk (Netherlands)

Review Editors
Pavel Kabat (Netherlands), Zbigniew Kundzewicz (Poland)

Volunteer Chapter Scientist
Asako Nishijima (Japan)

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Executive Summary

In the last decades, warming has caused a shift towards earlier maximum spring discharge, decreased spring snowpack and sometimes decreased magnitudes of snowmelt floods in regions with seasonal snow storage *(high confidence, high agreement, robust evidence)*. [3.2.3, 26.2.2] Where more winter precipitation falls as rain than snow, winter low flows have increased significantly. Where stream flow is lowest in summer, decreased snow storage has exacerbated summer low flows. River ice in Arctic rivers has been observed to break up earlier. [3.2.3]

Projected climate changes imply large changes in the frequency of floods *(high agreement, robust evidence)*. More frequent intense rainfall events (WG1 SOD 12.4.5.5) would increase the frequency of flooding in small catchments, but the implications for larger catchments are more uncertain because of the limited extent of the intense events. In some areas, reduced snowfall will reduce spring flood peaks. More people will be exposed to floods, notably in Asia, Africa, and Central and South America, and economic losses will increase due to both increased exposure and anthropogenic climate change *(high confidence, high agreement, limited evidence)*. Vulnerability can be reduced by adaptation.

Projected climate changes would change hydrological regimes substantially *(high agreement, robust evidence)*. Runoff and groundwater recharge are projected to increase at high latitudes and in the wet tropics, and to decrease in most dry tropical regions, controlled mainly by changes in precipitation. Changes in runoff are typically one to three times greater than changes in precipitation. Except in very cold regions, warming brings forward the snowmelt season, altering the seasonal regime. [3.4.5, 3.4.6]

Both increasing greenhouse-gas concentrations and climate change affect vegetation and thus transpiration, runoff and groundwater recharge *(high agreement, medium evidence)*. This impact is very uncertain and locally specific. The active role of vegetation is not considered in most hydrological studies. [Box CC-VW]

Glaciers will continue to lose mass, with meltwater yields from stored glacier ice eventually diminishing as the glaciers shrink *(high agreement, robust evidence)*. The rate of loss per unit of glacierized area will accelerate. The accumulation season will become shorter and the melting season longer, and in almost all regions total accumulation will decrease. In many regions meltwater production will increase during the next several decades but decrease thereafter. Glaciers have long response times and would continue to lose mass even if the climate were to cease to change. [3.4.4]

Drying of soils is projected in most dry regions *(medium confidence, high agreement)*. Projected changes in droughts depend partly on the definition of drought (WG1 SOD 12.4.5.3). [3.4.9]

Climate change is projected to reduce renewable water resources in most semi-arid and arid regions (*high agreement, robust evidence*). This constitutes a key risk, reducing food security. [3.5]

Climate change affects freshwater ecosystems by changing river flow regimes *(high agreement, limited evidence)*. Quantitative responses are known only in a few cases, but this ecological impact may be stronger than that of historic alterations due to human water withdrawals and dams. [3.5.2.4]

Certain approaches to reduce greenhouse-gas emissions imply greater risks for freshwater systems than others *(high agreement, limited evidence)*. Bioenergy crops can require larger amounts of water for irrigation than the amount of water for other mitigation measures. Hydropower has negative effects on freshwater ecosystems which can be reduced by appropriate management. Carbon capture and storage can decrease groundwater quality. In some regions, afforestation can reduce renewable water resources but also flood risk *(high agreement, limited evidence)*. [3.7.2.1]

Water quality changes are linked to warming, changes in rainfall, and climate-related erosion and deforestation (*high agreement, limited evidence*). Projections under climate change scenarios show a risk of deteriorating water quality for municipal supply, even with conventional treatment *(high agreement, limited evidence)*. [3.2.5; 3.5.2.3] Possible positive impacts include reduced risks of eutrophication and algal blooms when nutrients are flushed from lakes and estuaries by more frequent storms and hurricanes, *(high agreement, limited evidence)*. [3.2.5]

Climate change increases investment costs for water and wastewater treatment, while operating costs could rise or fall. Improved or even new water-treatment infrastructure may be needed to address variations in the quantity and quality of water *(high agreement, medium evidence*) but under warmer conditions water and wastewater treatment processes are likely to perform better *(low to medium agreement, limited evidence)*. [3.5.2.3; 3.6]

Hydrological impacts of climate change increase with increasing greenhouse-gas emissions *(high agreement, robust evidence)*. A low-emissions pathway reduces damage costs and costs of adaptation. Impacts of climate change on water resources are likely to reduce economic growth, particularly in developing countries (*high agreement, limited evidence*). [Table 3-2; 3.4; 3.5; 3.6.5]

Adaptive water management techniques offer an opportunity to address uncertainty due to climate change *(high agreement, limited evidence)*. Such techniques include scenario planning, employing experimental approaches that involve learning from experience, and the development of flexible solutions that are resilient to uncertainty. However, there are barriers such as lack of technical capacity, financial resources, awareness, communication, etc. [3.6.2; 3.6.6]

Adaptation to climate change in the water sector provides many opportunities for "no-regrets" improvements (*high agreement, limited evidence*). Of the global cost of adaptation, 85% is required in developing countries (*medium agreement, medium evidence*), in amounts similar to those estimated for the Millennium Development Goals [3.6.1; 3.6.5]. Annual global adaptation costs to maintain baseline levels of water-supply and sanitation services will be 50 to 70% of baseline investment in the sector (*high agreement, limited evidence)*. Some adaptive water-management measures also mitigate climate change (*medium agreement, low evidence*). For example wetland conservation increases carbon storage. [3.7.2]

3.1. Introduction

An adequate, secure water supply is essential for human well-being (Oki and Kanae, 2006), and changes in the hydrological cycle can generate different water-related hazards, and interact with non-climatic drivers and water management (Figure 3-1). Water is the delivering mechanism of climate change impacts to society even sectors on energy, agriculture, and transport. Even though water circulates on the Earth, it is a locally variable resource, and vulnerabilities to water-related hazards differ between regions.

[INSERT FIGURE 3-1 HERE
Figure 3-1: Framework for considering the impacts of climate change on freshwater systems and society. Socio-economic changes, such as GDP, population, and urbanization, will change the way of water managements, exposure and vulnerability of human beings against water related risks, and non-climatic drivers changing water management in terms of quantity and quality, as well as emissions and concentration of Green House Gases (GHGs) and Aerosol, that will lead to changes in precipitation, temperature, and sea level. Water management, non-climatic drivers, and climate change will alter hydrological cycles, and lead to change the impacts and risks for humans and ecosystems in conjunction with the changes in exposure and vulnerability, and hazards such as flood and drought. Water management consists with measures developing infrastructure, such as dykes, dams, and reservoirs, and non-structural measures, such as early warning system. Land cover and land use changes including afforestation, deforestation, and settlement, change of water demand due to economic development and demand changes in food and energy, and anthropogenic changes in pollutant load are examples of non-climatic drivers, and they are inter-acting each other. Mitigation acts on the emission and concentration of GHGs as well as on non-climatic drivers, while adaptation acts on non-climatic drivers and water management which alters exposure and vulnerability. (modified from Figure 3-1, AR4)]

Anthropogenic climate change is one of many stressors of water resources. Non-climatic drivers such as population increase, urbanization, economic development and land-use or natural geomorphic changes also challenge the sustainability of resources by decreasing water supply or increasing demand. In this context, adaptation options for climate change can be seen positively as options for improvement.

The key messages with *high* or *very high confidence* from the Working Group II Fourth Assessment Report (AR4; IPCC, 2007) in respect to freshwater resources were:

- The impacts of climate change on freshwater systems and their management are mainly due to observed and projected increases in temperature and sea level, local changes of precipitation, and changes in the variability of those quantities.
- Semi-arid and arid areas are particularly exposed.
- Higher water temperatures, increased precipitation intensity, and longer periods of low flow exacerbate water pollution, with impacts on ecosystems, human health, water services reliability and operating costs.
- Climate change affects the water-management infrastructure and practice.

- Adaptation procedures and risk-management practices have been developed for the water sector in some countries and regions.
- The negative impacts of climate change on freshwater systems outweigh its benefits.

This chapter assesses observed (Section 3.2) and projected future impacts (Section 3.4) of climate change on freshwater resources and their management, mainly based on research published since AR4. The drivers of hydrological change are summarized in Section 3.3. Impacts, vulnerabilities, and risks for human and environmental systems are assessed in Section 3.5; adaptation issues, including uncertainties and costs, in Section 3.6), and linkages with other sectors in Section 3.7. Current gaps in research and data are summarized in Section 3.8. For further information on observed trends in the water cycle, please see Chapter 2 of the Working Group I ("WGI") contribution to this assessment. See WGI Chapter 4 for freshwater in cold regions and WGI chapters 10 for detection and attribution, 11 for near-term projections, and 12 for long-term projections of climate change. In this Working Group II contribution, impacts on aquatic ecosystems are discussed in Chapter 4 (see also Section 3.5.2.4 below). Chapter 7 describes the impacts of climate change on food production (see also Section 3.5.2.1 for the impact of hydrological changes on the agricultural sector). The health effects of changes in water quality and quantity are covered in Chapter 11, and regional vulnerabilities related to freshwater in Chapters 21-30. Section 3.6.5 discusses impact costs and adaptation costs related to water resources; these costs are assessed more broadly in Chapter 10.

3.2. Observed Hydrological Impacts of Climate Change

3.2.1. Detection and Attribution

A documented hydrological change is not necessarily an impact of anthropogenic climate change. Detection entails showing that part of the documented change is not due to natural random or quasiperiodic variability of the water cycle. For robust attribution to climatic change, all the drivers of the hydrological change must be identified, with confidence levels assigned to their contributions. Human activities like water withdrawals, land-use change, pollution and water management mean that this is usually difficult. Nevertheless, many hydrological impacts can be attributed confidently to their climatic causes (Table 3-1). End-to-end attribution, from human climate-altering activities to impacts on freshwater resources, is not attempted in most studies, because it requires experiments with climate models in which the external natural and anthropogenic forcing is "switched off". However climate models do not currently simulate the water cycle at fine enough resolution for attribution of hydrological impacts to anthropogenic climate change. Until climate models and impact models become better integrated, it is necessary to rely heavily on multi-step attribution, in which hydrological changes are shown to be consistent with climatic changes that may in turn be attributable to human activities.

[INSERT TABLE 3-1 HERE
Table 3-1: Selected examples, mainly from Section 3.2, of the observation, detection and attribution of impacts of climate change on freshwater resources. Observed hydrological changes are attributed here to their climatic drivers, which are not all known to be anthropogenic; in the diagram, symbols with borders represent end-to-end attribution of the impact on resources to anthropogenic climate change.

1: Gedney *et al*. (2006a), Gerten *et al*. (2008); 2: Piao *et al*. (2010); 3: Shiklomanov *et al*. (2007); 4: Hidalgo *et al*. (2009); 5: Collins (2008); 6: Baraer *et al*. (2012); 7: Rosenzweig *et al*. (2007); 8: Min *et al*. (2011); 9: Pall *et al*. (2011); 10: Aguilera and Murillo (2009); 11: Jeelani (2008); 12: Evans *et al*. (2005); 13: Marcé *et al*. (2010); 14: Pednekar *et al*. (2005); 15: Paerl *et al*. (2006); 16: Tibby and Tiller (2007).]

Extreme hydrological events, such as floods, prompt speculation about whether they are "caused" by climate change. Climate change can indeed alter the probability of a particular event. However, to estimate the alteration reliably it is necessary to quantify uncertainties due to natural variability in the changed and the unchanged climates, and also – because of the need for model simulations – uncertainties due to limited ability to simulate the climate.

The probability or risk of the extreme event can be measured by recording the fraction of events beyond some threshold. Call this fraction r_{ctrl} in the actual climate and r_{expt} in the climate in which there is no anthropogenic climate change, and suppose there are many simulated, paired instances of r_{ctrl} and r_{expt}, with the ratio of risks given by $F = r_{expt}/r_{ctrl}$. The distribution of simulated risk ratios F is an estimate of the likelihood that the climate change has altered the risk.

Figure 3-2 illustrates the probabilistic character of attribution when uncertainty is multi-dimensional. It summarizes a formidable amount of computation, and it is not probable that such graphs will become routine tools for assessing single-event risks in, for example, the insurance industry. Nevertheless Figure 3-2 demonstrates consistency of weather with climate: anthropogenic greenhouse radiation made these floods much more likely. Reducing the computational cost of single-event attribution, possibly by identifying changes in event frequency, requires further study.

[INSERT FIGURE 3-2 HERE
Figure 3-2: Likelihood distributions of the ratio *F* of risks of flooding in England and Wales in autumn 2000 in several thousand paired simulations without and with anthropogenic greenhouse forcing (based on Pall *et al*., 2011; see also Bindoff *et al*., 2013 (WGI Chapter 10)). Each pair starts from a unique initial state that differs slightly from a common reference state. Vertical line represents no change in risk due to anthropogenic greenhouse forcing. Thin coloured lines: distributions with anthropogenic forcing, obtained with a seasonal-forecast model driven by patterns of attributable warming found beforehand from four climate-model simulations of the 20th century; the forecast model is coupled to a model of basin-scale runoff and hydraulics. Thick black line: aggregate of the four distributions.]

3.2.2. Precipitation, Evapotranspiration, Soil Moisture, Permafrost, and Glaciers

Global trends in precipitation from several different datasets during 1901-2005 are statistically insignificant (Bates *et al*., 2008; Hartmann *et al*., 2013 (WGI Chapter 2)); however, according to regional observations, most droughts and extreme rainfall events of the 1990s and 2000s have been the worst since the 1950s (Baringer *et al*., 2010) and certain trends in total precipitation and numerous indicators of precipitation extremes are observed (Hartmann *et al*., 2013 (WGI Chapter 2)). Recent changes in regional precipitation are attributed mainly to warming, which alters the atmospheric circulation (Lambert *et al*., 2004; Stott *et al*., 2010). Although the models substantially underestimate observed trends, Zhang *et al*. (2007) estimated that in the 20th century 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.

Changes in snowfall are indeterminate, as for precipitation, however, consistent with observed warming, a shortening of the snowfall season is observed for most of the Northern Hemisphere, together with shifts towards earlier start and later end dates of the snowmelt season (Takala *et al*., 2009; Tedesco *et al*., 2009).

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). Observed and estimated global and regional trends in evapotranspiration suggest intensification of the hydrologic cycle (Huntington, 2010). Due to changes in precipitation, in diurnal temperature range, aerosol concentration, (net) solar radiation, vapour pressure deficit, and wind speed, the rate of regional pan evaporation has been steadily decreasing since the 1960s (Fu *et al*., 2009; McVicar *et al*., 2010; Miralles *et al*., 2011; Roderick and Farquhar, 2002; Wang *et al*., 2011). No fundamental physically-based explanation has been provided for the so called “evaporation paradox” that an increase in evaporation is expected, but a decrease has been observed (Fu *et al*., 2009). The evaporation paradox is made more puzzling by robust oceanographic observations of changes in geographical patterns of salinity. Salty parts of the ocean have become saltier and fresher parts fresher, a change attributable only to a more intense water cycle and, with *high confidence*, to human forcing of climate (Pierce *et al*., 2012).

Long-term records of soil moisture content in natural conditions are available in limited regions, such as the former Soviet Union, China, and central USA (Bates *et al*., 2008; Wang *et al*., 2011). Robock *et al*. (2005) reported a long-term increase in summertime soil moisture in Ukraine. Regional downward and upward trends in soil moisture content have been calculated for China, where a trend to longer, more severe and frequent soil moisture droughts has been experienced over 37% of the land area (Wang *et al*., 2011). For example in South China, increases in dry days and a prolongation of dry periods have been detected (Fischer *et al.*, 2013; Gemmer *et al*., 2011), and can be attributed to increases in warm days and warm periods (Fischer *et al.*, 2011). These findings need to be considered carefully, as the results depend on the type of procedure used to obtain them (e.g. Sheffield and Wood, 2007).

Decreases in the extent of permafrost and increases in its average temperature are widely observed, for example in some regions of the Arctic and Eurasia (Comiso *et al*., 2013 (WGI Chapter 4)) and the Andes (Rabassa, 2009). Soil humidity in permafrost areas and permafrost degradation are strongly connected with the active-layer depth and influence the stability of steep slopes (Harris *et al*., 2009). The release of GHGs due to permafrost degradation can have unprecedented impacts on the climate, but these processes are not well represented in global climate models yet (Grosse *et al*., 2011).

Due to glacier retreat, the formation of new lakes in high-mountain regions is increasing and causes further environmental impacts (Frey *et al*., 2010). As examples of changes on land, fast glacier length and area recession, thinning of the ice cover and an increase of regional snowline elevation are observed in South America (Rabassa, 2009). Almost all small glaciers in the tropical Andes have been shrinking rapidly since the 1980s; current rates are unprecedened since the early 18th century (Rabatel *et al.*, 2013).

3.2.3. Runoff and Stream Flow

There is a general agreement between detected trends in streamflow and the observed regional changes in precipitation and temperature since 1950s. In Europe, streamflow decreased in the south and east and generally increased elsewhere (Stahl *et al*., 2010; 2012), particularly in northern latitudes (Wilson *et al*., 2010); In north America increases were observed in the Mississippi basin and decreases in the US Pacific Northwest and South Atlantic-Gulf regions (Kalra *et al*., 2008). In China, a decrease in streamflow in the Yellow River is consistent with a reduction of 12% in summer and autumn precipitation, whereas the Yangtze shows a small increase in annual runoff driven by an increase in monsoon rains (Piao *et al*., 2010). These and other stream flow trends must be interpreted with caution (Jones, 2011) because of confounding factors such as land-use changes (Zhang and Schilling, 2006), irrigation (Kustu *et al*., 2010) and urbanisation (Wang and Cai, 2010).

In a global analysis of simulated discharges (1948-2004), only about one-third of the top 200 rivers (including the Congo, Mississippi, Yenisei, Paraná, Ganges, Columbia, Uruguay, and Niger) showed significant trends in discharge; 45 recorded decreases and only 19 recorded increases (Dai *et al*., 2009). Decreasing trends in low and mid latitudes are consistent with recent drying and warming in West Africa, southern Europe, South and East Asia, eastern Australia, Western Canada and the USA and northern South America (Dai, 2013). Global increase in runoff has been linked to reduced transpiration due to a decrease of stomatal opening of many plant species at higher CO_2 concentration (Gedney *et al*., 2006b). However, these results are disputed (Peel and McMahon, 2006).

In regions with seasonal snow storage, warming has caused a shift towards earlier maximum spring discharge (*high agreement, robust evidence*) and has increased winter low flows because more winter precipitation falls as rain instead of snow (Clow, 2010; Korhonen and Kuusisto, 2010; Tan *et al*., 2011). There is *robust evidence* of earlier breakup of river ice in Arctic rivers (de Rham *et al*., 2008; Smith, 2000). Where the stream flow is lowest in summer, decreases have exacerbated summer dryness (Cayan *et al*., 2001; Knowles *et al*., 2006).

3.2.4. Groundwater

Attribution of observed changes in groundwater level, storage or discharge to climatic changes is difficult due to additional influences of land use changes and groundwater abstractions (Stoll *et al*., 2011). Observed trends are largely attributable to abstractions and other human actions not related to climate change. To what an extent groundwater abstractions have already been affected by climate change is not known. Detection of changes in groundwater systems and attribution to climatic changes is rare, also due to a lack of appropriate observation wells and a small number of studies. 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

Most studies published since the AR4 on observed impacts of climate on water quality refer to surface water bodies in high income countries, and cover intervals between 1 and 80 years. Some observed impacts of climate change on water quality are included in Table 3-1. Data for water quality is scarcer than for quantity. Impacts on water quality are linked to either seasonal or interannual variations in any of several variables, including ambient temperature, water temperature, precipitation and precipitation intensity. Droughts and the El Niño Southern Oscillation (ENSO) phenomenon can also affect water quality.

For lakes and reservoirs, the most frequently reported impacts are more intense eutrophication in warmer temperatures, shorter hydraulic retention times and higher nutrient loads resulting from increased storm runoff (*medium to high confidence, high agreement*). Higher runoff additionally results in higher loads of salts, faecal coliforms, pathogens and heavy metals (Paerl *et al.*, 2006; Pednekar *et al.*, 2005; Tibby and Tiller, 2007) (*medium to high confidence, medium to high agreement*; depending on the pollutant). Pathogens have associated impacts on health. For instance, hospital admissions for gastrointestinal illness in elderly people increased by about 10% when turbidity increased in the influent of a drinking water plant during high rainfall events, even though the water was treated in compliance with standards (Emelko *et al*., 2011; Schwartz *et al*., 2000) (*high agreement* based on *limited evidence, medium to high confidence*). In a reservoirin Spain (Marcé *et al.*, 2010), stream flow variations were of greater significance than temperature increasesin depleting the dissolved oxygen content. Possible positive impacts on water quality include reduced risks of eutrophication and algal blooms when nutrients are flushed from lakes and estuaries by more frequent storms and hurricanes (Paerl *et al*., 2008).

For rivers, all of the reported impacts reduced water quality. Greater runoff, instead of diluting pollution, sweeps pollutants , such as sediments, nutrients, organic matter, pathogens, salts and nutrients, from the soil into watercourses (*medium confidence, medium to high agreement*) (Benítez-Gilabert *et al*., 2010; Gascuel-Odoux *et al.*,2010; Howden *et al*., 2010; Loos *et al*., 2009; Macleod *et al*., 2012; Saarinen *et al*., 2010; Tetzlaff *et al.*, 2010). Some pollutants reduced dissolved oxygen concentrations. Increased organic matter content frequently impairs the quality of conventionally treated drinking water (Weatherhead and Howden, 2009) (*medium confidence, high agreement*). In streams in semiarid and arid areas, temperature changes have more impact than precipitation changes on the content of organic matter, nitrates and phosphorus (Benítez-Gilabert *et al.*, 2010; Chang, 2004; Ozaki *et al.*, 2003) (*medium confidence, medium agreement*).

Studies of groundwater quality are still limited. There are reports of elevated concentrations of faecal pollutants during the rainy season or after extreme rain events (*medium to high confidence, high agreement*), with varying response times. Due to impacts on health and the widespread use of groundwater for municipal supply this is an increasing source of concern (Jean *et al.*, 2006; Seidu *et al*., 2013). Faecal pollution during dry periods is extremely variable (Tetzlaff *et al.*, 2010), making any assessment difficult.

Linkages between observed effects on water quality and climate variability should be interpreted cautiously, at a local level, considering the type of water source and pollutant, the hydrological regime and the sources of pollution (*high confidence, high agreement*). Relationships between water quality and climatic variables are non-linear (except for temperature) and time-dependent (*medium confidence, medium agreement*). The pristine states of water systems need to be understood, since water sources are impacted upon for many reasons and effects may be long-lasting (Benítez-Gilabert *et al*., 2010; Howden *et al*., 2010; Kundzewicz and Krysanova, 2010; Senhorst and Zwolsman, 2005; Ventela *et al*., 2011; Whitehead *et al*., 2009a). If the observed deterioration of water quality continues, measures already in place to control point and non-point sources of pollution may be inadequate to deal with the negative impacts of climate change (*medium confidence, high agreement*).

[INSERT FIGURE 3-3 HERE
Figure3-3: Observations and projections of the impacts on the quality of water. (Note: This is not the final figure, it is still under production.)]

3.2.6. Soil Erosion and Sediment Load

Precipitation extremes in many regions have increased since 1950 (Seneviratne *et al*., 2012; their Table 3-2), which is expected to increase rainfall erosivity and to enhance soil erosion and sediment load. Warming may affect soil moisture, litter cover and biomass production, bring about a shift in winter precipitation from non-erosive snow to erosive rainfall, and increase melting of permafrost (Kundzewicz *et al*., 2007). The effects of climate change on soil erosion and sediment load are frequently obscure by impacts of human activities on river catchments (agriculture land use, grazing, water management; Walling, 2009).

In the Yellow River basin, where soil erosion results mostly from heavy rainfall events, reduced precipitation has contributed about 30% to a total reduction in sediment yield during 1970-2008, the remainder being attributable to water abstraction, sediment trapping in reservoirs and soil conservation measures (Wang *et al*., 2007; Miao *et al*., 2011). Dai *et al*. (2008), analyzing the decrease in sediment discharge of the Yangtze River over 1956-2002, found that climate change is responsible for an increase of about 3±2%, although on the side sediment decline dam construction (Three Gorges Dam) contributed 88±10% and soil conservation measures 15±5%.

Potential impacts of climate change on soil erosion and sediment production are of concern in regions with accelerated ice retreat either at high altitude or latitude (Walling, 2009). Glacial rivers are expected to discharge more meltwater, which may increase sediment loads. However, the *limited evidence* is inconclusive; there are both decreasing (e.g. Iceland; Lawler *et al*., 2003) and increasing trends (Patagonia; Fernandez *et al*., 2011). In the Himalayas and Tibetan Plateau, glacier areas have shrunk about 2-10% over the past 45 years but sediment yields from the Hindu Kush-Himalayas have decreased by half since the 1980s (from 4.3 Gt/year before the 1980s to <2.1 Gt/year; Li *et al*., 2008) due to intense human activities at altitudes below 500 meters (e.g. sediment retention in dams).

Detection of changes in the occurrence of landslides is complicated by incomplete inventories, both in time and space, and inconsistency in terminology. So far, there is no clear evidence that the frequency or magnitude of shallow landslides has changed over past decades (Huggel *et al*., 2012), even in regions with relatively complete event records (e.g., Switzerland; Hilker *et al*., 2009). Increased landslide impacts (measured by casualties or losses) in south, east, and southeast Asia, where landslides are predominantly triggered by monsoon and tropical cyclone activity, are largely attributed to population growth leading to increased exposure (Petley, 2012).

In summary, there is *low confidence* with *limited evidence* that anthropogenic climate change has made a significant contribution to soil erosion, sediment loads and landslides. The available records are limited in space and time, and evidence suggests that, in most cases, the human impacts are more significant than the impacts due to climate change.

3.2.7. Hydrological Extremes and Their Impacts

There is *low confidence*, due to *limited evidence*, that anthropogenic climate change has affected the frequency and magnitude of floods at global scale. The lack of robust evidence is mainly due to lack of long-term records from unmanaged catchments, most of those available being from headwaters, and the difficulty of attributing detected changes to climate or to human activities (Section 3.2.1). However, recent detection of changes in extreme precipitation and discharge trends (at some catchments) suggests an increased likelihood of flooding at regional scale (*medium confidence*). More locations and studies show increasing trends in heavy precipitation than those recording a decrease (Seneviratne *et al*., 2012), and flood-damage costs worldwide have been increasing since the 1970s, although partly due to increasing exposure of people and assets (Handmer *et al.*, 2012).

There is no strong evidence for trends in flooding in the USA (Hirsch and Ryberg, 2012), Europe (Benito and Machado, 2012; Kundzewicz, 2013; Mudelsee *et al*., 2003), UK (Hannaford and Hall, 2012), South America, and Africa (Conway *et al*., 2009). However, at smaller spatial scales, increases in flood magnitude and frequency have been detected in parts of northwestern Europe (Giuntoli *et al*., 2012; Hattermann *et al*., 2012; Petrow and Merz, 2009a), while a decrease in frequency was observed in the Pyrenees (Giuntoli *et al*., 2012; Renard *et al*., 2008). Flood discharges in the lower Yangtze region showed an upward trend in the last 40 years (Jiang *et al*., 2008; Zhang *et al*. 2009), and both upward and downward trends were identified in four basins in the northwestern Himalaya (Bhutiyani *et al*., 2008). In Australia, only 30% out of 491 gauge stations showed trends at the 10% significance level, with decreasing magnitudes in southern regions and increasing magnitudes in the northern regions (Ishak *et al*., 2010). In snow-melt dominated regions, there is no compelling evidence of widespread change in flood magnitude in Arctic rivers (Shiklomanov *et al*., 2007) or in Nordic rivers (Wilson *et al*., 2010). Cunderlik and Ouarda (2009) reported significant trends, most of them decreases, in snowmelt-flood magnitudes at almost one fifth of 160 stations. Similar decreases were found for spring and annual maximum flows (Burn *et al*., 2010).

Attribution has been addressed by Hattermann *et al*. (2012), who identified parallel trends in precipitation extremes and flooding in Germany, which for the increasing winter floods are explained in terms of increasing frequency and persistence of circulation patterns favourable to flooding (Petrow *et al*., 2009b). It is *very likely* that the observed intensification of heavy precipitation is largely anthropogenic (Min *et al.*, 2011; see also Section 3.2.1).

There is *high confidence* that socio-economic losses from flooding are increasing, although attribution of the losses to anthropogenic climate change is seldom established (Handmer *et al*., 2012; Kundzewicz *et al*., 2013). Attribution of losses is highly uncertain due to *limited evidence* (Bruce, 1999; Höppe and Grimm, 2009; Mills, 2005; Malmstadt *et al*., 2009; Schmidt *et al*., 2009). There is *high agreement*, but *medium evidence*, that greater exposure of people and assets, and societal factors is related to population and economic growth, contribute to the increased losses (Bouwer *et al*., 2007; Changnon, 2001; Pielke *et al*., 2005). Several studies normalize the loss records for changes in exposure and vulnerability (Bouwer, 2011). Most find no contribution of flooding trends to the trend in losses (Barredo, 2009; Benito and Machado, 2012; Hilker *et al*., 2009), although increased flood-related losses are found for China (Jiang *et al*., 2005) and Korea (Chang *et al*., 2009). However these studies, mostly at country level, do not take into account the regional diversity of trends seen in some long-term peak flow records (Section 3.2.3).

The definition of drought or local dryness (Seneviratne *et al.*, 2012; their Box 3-3) depends upon different perspectives (meteorological, hydrological, and agricultural), the variables considered relevant (precipitation, temperature, evapotranspiration, soil humidity) and the chosen index (e.g., Palmer drought severity index (PDSI), consecutive dry days (CDD), simulated soil moisture anomalies (SMA)).The AR4 (Trenberth *et al*., 2007) reported that the global extent of very dry areas (PDSI ≤ -3.0) more than doubled since the 1970s, and that droughts have increased since then particularly in the tropics and sub-tropics (Dai *et al*., 2004). There is substantial uncertainty in drought analyses based on indirect indexes such as the PDSI (Hartmann *et al*., 2013 (WGI Chapter 2); Dai, 2013; Sheffield *et al*., 2012). In a revised assessment using indices such as CDD and SMA rather than the simple PDSI, Seneviratne *et al.* (2012) found that some regions of the world, notably southern Europe and west Africa, have experienced trends toward more intense and longer droughts, while others (e.g. Central North America and Northwestern Australia) exhibited opposite trends (*medium confidence*). They attributed these patterns to anthropogenic influence on precipitation and temperature (*medium confidence*), although with *low confidence* for single regions.

Regarding vulnerability, some studies detect large supply-side reductions due to climate change that may stress existing water systems (Vanham *et al*., 2009), and others show how small reductions can be managed by existing supply systems or by moderate increases in adaptive capacity (Li *et al*., 2010).

3.3. Drivers of Change for Freshwater Resources

3.3.1. Climatic Drivers

Precipitation and potential evaporation are the main climatic drivers controlling freshwater resources. Precipitation is strongly related to the water-vapor content or specific humidity of the atmosphere, because saturation specific humidity depends on temperature: warmer air can hold much more water vapor. 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 (WGI Chapter 2)). This need not imply either more precipitation or more actual evaporation, although commonly both do increase. Among other climatic drivers are atmospheric carbon dioxide (Section 3.2.3) and deposited black carbon and dust (Box 3-1 in Section 3.4.4). Both of the latter, in even very small concentrations, enhance melting of snow and ice markedly by reducing the surface albedo.

The evolution of the climatic drivers is uncertain mainly because of: (1) internal variability of the atmospheric system; (2) inaccurate modelling of the atmospheric response to external forcings (for example anthropogenic greenhouse radiation, solar and volcanic influences, and changes of land use and land cover); and (3) the external forcing itself, as expressed in the range of outcomes from the chosen emissions scenarios. Internal variability and variation between models account for all of the uncertainty in precipitation in the first few decades of CMIP5 projections (Figure 3-4). The contribution of internal variability diminishes progressively. By no later than mid-century, discrepancies between models account for most of the uncertainty in precipitation, but the uncertainty in temperature (Kirtman *et al*., 2013 (WGI Chapter 11)) is due mostly to divergent scenarios, which never contribute more than one third to the uncertainty in 21st-century precipitation. Uncertainty due to downscaling of the output of climate models, and to the hydrological models themselves, is addressed in Section 3.4.1.

[INSERT FIGURE 3-4 HERE
Figure 3-4: Variance in projections of changes in decadal-mean precipitation for boreal summer (June, July, and August), decomposed into contributions from three sources of uncertainty. Simulations were for 2000-2100 under the SRES A1B, A2 and B1 scenarios, with one ensemble member taken from each of 14 CMIP3 GCM experiments. From Hawkins and Sutton (2011).]

CMIP5 simulations of the water cycle during the 21st century, with constraints from 20th-century observations, can be summarized as follows (Collins *et al*., 2013 (WGI Chapter 12)):

- Surface temperature, which affects the vapor-carrying capacity of the atmosphere and the ratio of snowfall to precipitation, increases by about 1.5 times more over land than over ocean (*very high confidence*).
- Warming is greatest over the Arctic (*very high confidence*), implying zonally variable changes in snowmelt and glacier mass budgets.
- Less precipitation falls as snow and the extent and duration of snow cover decrease (*high confidence*). In the coldest regions, however, increased specific humidity due to warming means that increased winter snowfall outweighs increased summer snowmelt.
- Wet regions become wetter and dry regions become drier (*medium confidence*), although one observational analysis (Sun *et al.*, 2012) is discordant; moreover the models tend to underestimate observed trends in precipitation (Noake *et al*., 2012) and its observed sensitivity to temperature (Liu *et al.*, 2012).
- Precipitation tends to increase in equatorial, middle and high latitudes and to decrease in subtropical latitudes (*medium to high confidence*), and global average precipitation increases (e.g. Collins *et al*., 2013 (WGI Chapter 12), their Figure 12-41). Precipitation changes become statistically significant only when temperature rises by at least 1.1-1.4°C (Mahlstein *et al.*, 2012). In many regions, projected 21st-century changes lie within the range of late-20th-century natural variability.
- Models consistently project decreases of precipitation in the Mediterranean, Mexico and central America, and parts of Australia, and increases in India and north and central Asia (*high confidence*).
- Evaporation increases almost everywhere, especially at higher northern latitudes and generally in concert with precipitation (Collins *et al*., 2012 (WGI Chapter 12), their Figure 12-25). This leads to decreases of soil moisture in many regions, particularly central and southern Europe, southern North America and southern Africa (*medium confidence*; Collins *et al*., 2013 (WGI Chapter 12), their Figure 12-23).

More intense extreme precipitation events are expected (IPCC, 2012). Among proposed reasons, one is the projected increase in specific humidity: intense convective precipitation in short periods (less than 1 hour) tends to “empty” the atmospheric column (Utsumi *et al.*, 2011; Berg *et al.*, 2013). Annual maxima of daily precipitation that are observed to have 20-year return periods in 1986-2005 are projected to have return periods in 2081-2100 that are shorter in proportion to the intensity of forcing: about 15 (RCP(representative concentration pathway)2.6), 11 (RCP4.5) and 6 (RCP8.5) years (Kharin *et al.*, 2013). Unlike annual mean precipitation, for which the simulated sensitivity to warming is typically 1.5-2.5 % K^{-1}, the 20-year return amount of daily precipitation typically increases at 5-9 % K^{-1}. Agreement between GCM-simulated extremes and reanalysis extremes is good in the extra-tropics but poor in the tropics, where there is *robust evidence* of greater sensitivity (10±4 % K^{-1}; O’Gorman, 2012). In spite of the intrinsic uncertainty of sampling infrequent events, variation between GCMs is the dominant contributor to uncertainty.

GCM-simulated changes in the incidence of meteorological droughts vary widely, so that there is at best *medium confidence* in projections (Seneviratne *et al.*, 2012). 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

In addition to climate change, the future of freshwater systems will strongly be impacted by demographic, socio-economic and technological changes, including lifestyle changes. Given the large uncertainty of climate models in translating emissions scenarios into projections of climatic change, a wide range of possible future development of non-climatic drivers is compatible with a wide range of climate change (Moss *et al*., 2010) particularly in terms of the number of population under high water stress (Kiguchi *et al*., 2013). This means that certain projected hydrological changes (Section 3.4) can occur under a wide range of future demographic, social, economic and ecological conditions, and thus may lead to very different impacts and vulnerabilities (Section 3.5). Therefore, the five shared socioeconomic pathways (SSP) socio-economic scenarios, which include narratives and quantifications of population and economic development (IIASA, 2012), can be combined with more than one GHG emissions scenario (representative concentration pathway (RCP)) (Moss *et al*., 2010).

Of particular importance for freshwater systems is the future agricultural land use, and in particular irrigation, as irrigation accounts for about 90% of global water consumption and severely impacts freshwater availability for humans and ecosystems (Döll, 2009). Due to mainly population and economic growth but also due to climate change, irrigation may significantly increase in the future. The share of irrigation from groundwater is expected to increase due to increased variability of surface water supply (Taylor *et al*., 2012a).

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. They illustrate the benefits of reducing GHG emissions for the Earth’s freshwater systems.

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

3.4.1. Methodological Developments in Hydrological Impact Assessment

Since the AR4 many assessments of the potential impact of climate change on hydrological characteristics have been published. Most have applied a now-standard methodology to estimate impacts, using information from climate models to perturb a baseline weather record and a hydrological model to simulate river flows, recharge or water quality (see Section 3.6.3 for methods to estimate impacts specifically for water management purposes).

Most climate change impact assessments have been based on the use of a small number (five or fewer) of climate scenarios. An increasing number has used larger ensembles from the AR4 CMIP3 scenario set (Arnell, 2011b; Arnell and Gosling, 2013a; Bae *et al*., 2011; Chiew *et al*., 2009; Gosling *et al*., 2010; Jackson *et al*., 2011) or ensembles of regional and global climate models (Kling *et al*., 2012; Olsson *et al*., 2011). Some studies have developed "probability distributions" of future impacts by combining results from multiple climate projections (see Section 3.6.3) and, sometimes, different emissions scenarios, making different assumptions about the relative weight to give to each scenario (Brekke *et al*., 2009b; Christierson *et al*., 2012; Manning *et al*., 2009). These studies conclude that the relative weightings given are typically less important in determining the distribution of future impacts than the initial selection of climate models considered.

Most assessments have used a hydrological model with the 'delta-method' to create scenarios, applying projected changes in climate derived from a climate model either to an observed baseline or with a stochastic weather generator; several such downscaling methods have been developed (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. An increasing number of studies (Fowler and Kilsby, 2007b; Kling *et al*., 2012; Veijalainen *et al*., 2012) have run models with input data produced by bias-correcting regional or global climate model data (Piani *et al*., 2010; van Pelt *et al*., 2009; Yang *et al*., 2010); unlike the delta method, this means that the simulated future weather incorporates changes in variability as projected by the regional model. On the contrary, the delta method only can reflect the projected changes of the mean state and cannot reflect the changes in variability, and various methodologies are proposed and their characterstics are compared. The choice of bias-correction method can cause discrepancy in the results as a choice of emission scenario or GCM (Watanabe *et al*., 2012). 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.

The effects of hydrological model parameter uncertainty are typically 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 (Arnell, 2011b; Cloke *et al*., 2010; Lawrence and Haddeland, 2011; Steele-Dunne *et al*., 2008; Teng *et al*., 2012; Vaze *et al*., 2010). However, several new studies suggest that the effects of model structural uncertainty can be substantial (Dankers *et al*., 2013; Davie *et al*., 2013; Haddeland *et al*., 2011; Hagemann *et al*., 2012; Schewe *et al*., 2013), due primarily to different representations of evaporation and snowmelt processes. Two global-scale multi-model studies on projected mean annual river runoff or discharge used the output of three (five) GCMs to drive eight (eleven) global hydrological models (Hagemann *et al*., 2012; Schewe *et al*., submitted). It was found that that hydrological and climate models contribute to the overall uncertainty of projected changes of runoff (discharge) water flows to similar extents globally, with distinct spatial patterns of dominance. The uncertainty of projected actual evapotranspiration, however, was determined to be dominated by the hydrological models.

The vast majority of published impact assessments have followed the conventional scenario-driven approach. Other approaches are, however, feasible. Cunderlik and Simonovic (2007) 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 in a catchment in Turkey. The advantage of this approach is that it is not necessary to use the hydrological model to simulate future hydrological characteristics. Another scenario-independent approach constructs response surfaces relating sensitivity of a hydrological indicator to changes in climate. Several studies have used a water-energy balance framework (based on Budyko's hypothesis and formula) to characterise the sensitivity of average annual runoff to changes in precipitation and evaporation (Donohue *et al*., 2011; Renner and Bernhofer, 2012a; Renner *et al*., 2012b). Prudhomme *et al*. (2010) constructed a response surface showing change in flood magnitudes by running a hydrological model with systematically-varying changes in climate. Not only does this approach show sensitivity of a system to change, it also allows rapid assessment of impacts under specific climate scenarios which can be plotted on the response surface.

3.4.2. Evapotranspiration

Based on global and regional climate models as well as physical principles, it is projected that global evapotranspiration is very likely to increase in a warmer climate resulting in an acceleration of the hydrologic cycle (Collins *et al*., 2013 (WGI Chapter 12)). Many uncertainties in both magnitude and direction of long-term trends are apparent. Evapotranspiration is not only affected by rising temperatures but also by changing radiation, changes in soil water content, decreases in bulk canopy conductance associated with rising CO_2 concentrations and climate change related vegetation changes (Box CC-VW; Katul and Novick, 2009).

An important source of uncertainty in hydrological projections is the response of empirically estimated potential evapotranspiration (PET) to climate change. Kingston *et al*. (2009) using six different methodologies suggest an increase in PET associated with a warming climate. Ekström *et al*. (2007) found that the Blaney-Criddle formulation lead to smaller changes than the Penman-Monteith formula. However, differences in the PET climate change signal of over 100% are found between the methods, with an uncertainty of 20% to 40% to the observed baseline period (1961-1990).

3.4.3. Soil Moisture and Permafrost

Potential evaporation, which would reduce soil moisture, is projected to increase particularly in southern Europe and Central America, Southern Africa and Siberia (Seneviratne *et al.*, 2010). Lower soil moisture increases the risk of extreme hot days (Hirschi *et al.*, 2011; Seneviratne *et al.*, 2006) and heat waves. For a range of scenarios, low soil moisture episodes of 3-6 month duration double in extent and frequency, and droughts longer than 12 months become three times more common, between the mid-20th century and the end of the 21st century. This is particularly the case where reductions in soil moisture are projected (Sheffield and Wood, 2008). Strong natural variability in drought occurrence and intensity makes the generally monotonic increases statistically not different from current climate.

Changes consistent with warming are also evident in the freshwater systems and permafrost ofnorthern regions. The area of permafrost is projected to continue to decline over the first half of the 21st century in all emissions scenarios (see Figure 4-18 in Chapter 4). In the RCP2.6 scenario of an early stabilization of CO_2 concentrations, permafrost area is projected to stabilize at near 20% below the 20th century area, and then begin to increase slightly.

3.4.4. Glaciers

All projections for the 21st century (Church *et al*., 2013) show continued mass loss from glaciers. In glacierized catchments, runoff reaches an annual maximum in summer, not spring as in snow-covered catchments. As the glaciers shrink, their relative contribution decreases and the annual runoff peak shifts towards spring (e.g., Huss, 2011). This shift is expected with *very high confidence* as an impact of warming. The relative importance of high-summer glacier meltwater can be substantial, for example 25% of August discharge in basins draining the European Alps, with area 10^5 km^2 and only 1% glacier cover; high-summer water supply will therefore be reduced noticeably by the projected glacier shrinkage (based on regional scenarios derived from the SRES A2 and B2 scenarios) to only 12% of 2008 extent by 2100 (Huss, 2011). Glacier meltwater also increases in importance during droughts and heat waves (Koboltschnig *et al*., 2007).

If warming proceeds at a constant rate then if, as expected, melting of stored glacier ice per unit area increases and total glacierized area decreases, the total water yield passes through a maximum: “peak meltwater”. Peak-meltwater dates have been projected between 2010 and 2050 (different regions of China; Xie *et al.*, 2006); 2010-2040 (European Alps; Huss, 2011); and 2060-2080 (the world; Radić and Hock, 2011). Pending further regional-scale investigations, there is *medium confidence* that the peak response to 21st-century warming will fall within the century in most inhabited glacierized regions, where at present society is benefitting from a transitory “meltwater dividend”. Variable climatic forcing leads to complex variations of both the melting rate and the extent of glacier ice, which depend on each other. Peak meltwater can therefore be difficult to identify, but it has been detected with *medium confidence* in some studies (Table 3-1).

If they are in long-term equilibrium, glaciers reduce the interannual variability of 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 diminishing influence may make the water supply less dependable.

_____ START BOX 3-1 HERE _____

Box 3-1. Case Study: Himalayan Glaciers

Like glaciers elsewhere (Comiso *et al*., 2013 (WGI Chapter 4); their FAQ 4.1), Himalayan glaciers are losing mass. They are therefore of growing concern because they are important resources of freshwater for their host countries (Bhutan, China, India, Nepal and Pakistan). The total resource of ice is known only roughly; estimates range from 2100 to 5800 Gt (Bolch *et al*., 2012).

Himalayan glacier mass budgets have been negative on average for the past five decades. The loss rate may have become greater after about 1995, but it has not been greater in the Himalaya than elsewhere (Figure 3-5). A recent large-scale measurement, highlighted in the figure, is the first well-resolved, region-wide measurement of any component of the Himalayan water balance. It suggests strongly that the conventional measurements are not representative of the regional average. Thus Figure 3-5 also illustrates the uncertainty of generalizations from sparse data.

[INSERT FIGURE 3-5 HERE
Figure 3-5: A compilation of all published glacier mass balance measurements from the Himalaya (based on Bolch *et al*., 2012). Each measurement is shown as a box of height ±1 standard deviation centred on the average balance (±1 standard error for multi-annual measurements). Region-wide measurement (Kääb *et al*., 2012) was by satellite laser altimetry. Global average (Comiso *et al*., 2013 (WGI Chapter 4)) is shown as a 1-sigma confidence region.]

Radić *et al*. (2013) projected glacier mass changes for 2006-2100 by simulating the response of a glacier model (Radić and Hock, 2011) to CMIP5 projections from 14 GCMs under scenario RCP4.5. Results for the Himalaya range between 2% gain and 29% loss to 2035; to 2100, the range of losses is 15-78%. The model-mean loss to 2100 is 45% under RCP 4.5 and 68% under RCP8.5 (*medium confidence*). It is *virtually certain* that these projections are more reliable than an earlier suggestion of complete disappearance by 2035 (Cruz *et al*., 2007). At the catchment scale, however, 21st-century projections do not yet present a coherent region-wide picture.

For an imposed warming rate of 0.06 K/year, 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). The GCM-forced simulations of Immerzeel *et al*. (2012) in eastern Nepal, in contrast, show runoff increasing throughout the century because increased precipitation over-compensates for the loss of ice; because the monsoon and the melt season coincide here, there is no seasonal shift of peak discharge.

The growing atmospheric burden of anthropogenic black carbon implies reduced glacier albedo, and measurements in eastern Nepal (Yasunari *et al*., 2010) suggest that this could yield 70-200 mm/year of additional meltwater. In global terms, the Himalaya and southern Tibet are a hotspot for deposition of soot, which may outweigh the greenhouse effect as a radiative forcing agent for snowmelt (Qian *et al*., 2011).

Moraine-dammed ice-marginal lakes continue to cause concern (Fujita *et al*., 2009). In the western Himalaya, they are small and stable in size, while in Nepal and Bhutan they are more numerous and larger, and most are growing (Gardelle *et al*., 2011). Thus the hazard has increased, but there has been little progress on the predictability of dam failure.

Himalayan glacier meltwater is an increasing, and during this century is expected to become a decreasing, component of a complex mix of sources of freshwater. Its relative contribution to water resources decreases with distance downstream, being greatest where it enters seasonally arid regions such as the lower Indus, and becoming negligible in the monsoon-dominated Ganges-Brahmaputra (Kaser *et al*., 2010). 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 3-1 HERE _____

3.4.5. Runoff and Stream Flow

Since the publication of the AR4 there have been very many catchment-scale studies of the potential impacts of climate change on runoff and streamflow, and many of the spatial gaps identified in AR4 have been plugged to a very large extent. Virtually all of these studies have estimated impacts using scenarios constructed from climate models. The projected impacts in a catchment depend on the sensitivity of the catchment to change in climatic characteristics and on the projected change in the magnitude and seasonal distribution of precipitation, temperature and evaporation. Catchment sensitivity is largely a function of the ratio of runoff to precipitation; sensitivity is greater the smaller the ratio. Figure 3-6 shows projected change in mean monthly runoff for seven catchments across the globe, using the same seven climate model patterns scaled to represent an increase in global mean temperature of 2°C above the 1961-1990 mean (Arnell, 2011b; Hughes *et al*., 2011; Kingston and Taylor, 2010; Kingston *et al*, 2011; Nobrega *et al*, 2011; Thorne, 2011a; Xu *et al*., 2011); changes under the HadCM3 model with 2 and 4°C increases are highlighted. The figure illustrates how the same climate model has a different effect in different catchments, shows considerable variability in estimated impact in each catchment across the seven scenarios and also show non-linear response to increasing forcing (in the Mitano catchment). The uncertainty is largely driven by differences in projected changes in precipitation between different climate models. Incorporating uncertainty in hydrological model structure (Section 3.4.1) would increase further the range in projected impacts at the catchment scale.

[INSERT FIGURE 3-6 HERE
Figure 3-6: Range in change in mean monthly runoff across seven climate models in seven catchments, with a 2°C increase in global mean temperature (above 1961-1990) (Arnell, 2011b; Hughes *et al*., 2011; Kingston and Taylor, 2010; Kingston *et al*., 2011; Nobrega *et al*., 2011; Thorne, 2011a; Xu *et al*., 2011). Changes with the HadCM3 climate model with increases of 2 and 4°C are highlighed.]

A number of studies have used projected changes in runoff and streamflow across the global domain (e.g. Arnell and Gosling, 2013a; Döll and Zhang, 2010; Fung *et al*., 2011; Gosling *et al*., 2010; Schewe *et al*., 2013), and some assessments have used directly the output from global climate models (Hirabayashi *et al*., 2008; Okazaki *et al*., 2012; Tang and Lettenmaier, 2012). (Figure 3-7). Most of these studies have used CMIP3 climate models, although a small number (Okazaki *et al*., 2012; Schewe *et al*., 2013) have used CMIP5 models. 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 projected to increase at high latitudes and in the wet tropics, 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 are 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]. Changes in average annual runoff are typically between 1 and 3 times as large as changes in average annual precipitation (Tang and Lettenmaier, 2012).

[INSERT FIGURE 3-7 HERE
Figure 3-7: Relative change in annual discharge at 2°C (2.7°C above pre-industrial) compared to present-day, under RCP8.5. Color hues show the multi-model mean change, and saturation shows the agreement on the sign of change across all 55 GHM-GCM combinations (percentage of model runs agreeing on the sign). (Schewe *et al*., 2013)]

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 regions areas where increases in precipitation are sufficient to result in increased, rather than decreased snow accumulation during winter. The greatest changes are found near the boundaries of regions which currently experience considerable snowfall, where the marginal effect on snowfall and snowmelt of higher temperatures is greatest.

3.4.6. Groundwater

While the relation between groundwater and climate change was rarely investigated before 2007, the number of relevant studies and review papers (Green *et al*., 2011; Taylor *et al*., 2012a) has since then increased significantly. Ensemble studies of the impact of climate change on groundwater recharge and partially also groundwater levels were done for the globe (Portmann *et al*., 2013), all of Australia (Crosbie *et al*., 2012), the German Danube basin (Barthel *et al*., 2010), and aquifers in temperate Belgium and England (Goderniaux *et al*., 2011; Jackson *et al*., 2011), the Pacific coast of the USA and Canada (Allen *et al*., 2010) and for a study site in the semi-arid part of the USA (Ng *et al*., 2010). The number of applied climate models ranged from 4 to 20, and with two exceptions, 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 areas, and the range of percent changes of projected groundwater recharge mostly exceed the range of projected precipitation changes.

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 and thus renewable groundwater resources are projected to increase (or decrease) (Kundzewicz and Döll, 2009). Changes in precipitation intensity affect groundwater recharge as a fraction of total runoff. Increased precipitation intensity, for example, may decrease groundwater recharge due to exceedance of infiltration capacity (typically in humid areas) or increase it due to a fast percolation through the root zone from where water otherwise would be evapotranspired (typically in semi-arid areas) (Taylor *et al*., 2012b; Liu, 2011). The response of groundwater recharge and levels to climate change is small in case of fine-grained soils and clayey confining layers, and large in case of sandy soils and water table aquifers (van Roosmalen *et al*., 2007). It also depends on the vegetation, in particular as vegetation adapts to climate change and thus modifies the groundwater response to climate change (Box CC-VW).

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). Due to expected increases in precipitation and streamflow variabililty, climate change is also expected to lead to increased groundwater abstractions (Taylor *et al*., 2012a), lowering groundwater levels and storages.

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 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 *likely* to suffer from saltwater intrusion and a loss of freshwater volume (Werner *et al*., 2012; Masterson and Garabedian, 2007). Assuming an average salt water density of 1.025 g/cm^3, the thickness of the unconfined freshwater layer decreases by roughly 40 meters if difference between the fresh groundwater table and the sea level is decreased by 1 meter due to either sea level rise or decreased groundwater recharge (Werner *et al*., 2012). Salt water intrusion is mostly a very slow process that may take several centuries to reach equilibrium (Webb and Howard, 2011).

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 is also affected by storm surges, with increased upstream transport of saline waters in the rivers which then contaminate the underlying fresh groundwater from above (Masterson and Garabedian, 2007). 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).

Changes in groundwater recharge also affect streamflow in rivers. In a catchment of the Upper Nile basin in Uganda, mean global temperature increases of 4°C or more are 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). Changing groundwater tables have an effect on land surface fluxes and thus the climate system which remains to be fully explored (Jiang *et al*., 2009). However, it has been shown that the effect to be strongest in case of semi-arid condition where the groundwater table is less than 7 meter below the ground (Ferguson and Maxwell, 2010).

3.4.7. Water Quality

The impact of climate change on the quality of water occurs through a complex set of natural and anthropogenic mechanisms working in parallel and in series and, occasionally, even at the same time. Projecting future conditions is a difficult task involving the integration of climate models outputs with those used to analyze the transportation and transformation of pollutants in water, soil, and air (Andersen *et al*., 2006; Arheimer *et al*., 2005; Bonte and Zwolsman, 2010; Ducharne, 2008; Marshall andRandhir, 2008; Rehana and Mujumdar, 2012; Towler *et al*., 2010; Trolle *et al*., 2011; Wilby *et al*., 2006). In addition, such models use different scales and have to be adapted and calibrated to local conditions; often a difficult task due to a lack of sufficient and appropriate information. As a result, there is little in the literature with regard to the future impacts of climate change on water quality, and this is available where the uncertainty is high.

From the projections reported (Figure 3-3), it is evident that results are highly dependent on (Bonte and Zwolsman, 2010; Chang, 2004; Kundzewicz and Krysanova, 2010; Sahoo *et al*., 2010; Trolle *et al*., 2011; Whitehead *et al*., 2009a; 2009b) (a) local conditions; (b) climatic and environmental assumptions, such as other types or sources of pollution; and (c) current impacts (i.e., pollution state/reference state). Most projections are useful in affirming that observed impacts will be *likely* to prevail in the future for natural and artificial reservoirs (Bonte and Zwolsman, 2010; Brikowski, 2008; Ducharne, 2008; Loos *et al*., 2009; Marshall andRandhir 2008; Qin *et al*., 2010; Sahoo *et al*., 2010; Trolle *et al*., 2011), rivers (Andersen *et al*., 2006; Bowes *et al*., 2012; Whitehead *et al*., 2009a; 2009b) and groundwater (Butscherand Huggenberger, 2009; Rozemeijer *et al*., 2009), and will be a result of the combination of the change and variations in air/water temperature and precipitation/storm runoff, combined with many other factors that also impact upon the quality of water (Chang, 2004; Whitehead *et al*., 2009a).

3.4.8. Soil Erosion and Sediment Load

Heavy rainfall events are *likely* to increase in the 21st century over many areas on the globe (Seneviratne *et al*., 2012), which may lead to a disproportionate amount of erosion relative to the total rainfall contribution. At global scale, changes in soil erosion in the 2090s compared to the 1980s is expected to increase about 14% (9% attributed to climate and 5% due to land use) with significant increase of 40-50% in Australia and Africa (Yang *et al*., 2003). The largest amounts are expected on erosion-prone semiarid areas where contribution of extreme events may constitute up to 40% of total erosion (Baartman *et al*., 2012). In agricultural lands of temperate regions, soil erosion may respond in complex non-linear ways; for instance in agricultural land on the UK South Downs a rainfall scenario of 10% increase in winter rainfall could give increases of annual erosion by up to 150%, that is be explained by the interaction of the timing of rainfall (winter) during the early growing season (Favis-Mortlock and Boardman, 1995). On the other hand, in central Europe (Austria) regional climate model HadRM3H (SRES A2, 2010-2099) projects a net-decrease of rainfall amount of 10-14% in erosion sensitive months giving rise to decline in soil erosion in all tillage systems by 11-24% (Scholz *et al*., 2008). Land management practices are critical to reduce soil erosion under projected climate change. In the China's Loess Plateau, GCMs project a soil erosion increase of 5-195% during 2010-2039 under conventional tillage, whereas under conservation tillage shows decreases of 26-77% (Li *et al*., 2011).

Climate change is *likely* to affect sediment load in rivers through soil erosion processes, water discharge, and changes in land use and land cover. For example, an increase in water discharge of 11-14% in two Danish rivers was projected to raise the annual suspended sediment between 9% and 36% during the period 2071-2100 (Thodsen *et al*., 2008). Projected river's sediment flux in response to climate change needs also to consider the sensitivity of land cover to climate change. For instance, Gomez *et al*. (2009) simulated the changes in water flow and suspended sediment flux in the Waipaoa River in New Zealand showing that climate change may reduce the mean flow by 13% in the 2030s and 18% in the 2080s, producing changes of annual suspended sediment flux of ±1 Mt/year by the 2030s, but depending on the climate change scenario by the 2080s it may either decline by 1 Mt/year (under warmer drier conditions) or increase by 1.9±1.1 Mt/year (warmer but not substantially drier). Increases in total precipitation amount, along with melting glaciers, 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, an increased precipitation and enhanced melting of glaciers will increase sediment yield by 26% by 2050 (Neupane and White, 2010). In the tropical regions, the intensity of stronger storms from cyclones was projected to increase 2-11% by 2100 (Knutson *et al*., 2010).

In summary, projected increase in heavy rainfall and temperature changes are *very likely* to produce changes in soil erosion and sediment yield; however, overall there is a *low confidence* on the rate of these changes due to the non-linear response of soil erosion and its high dependence on land cover. There impacts of climate change in soil erosion is expected to double the one induced by land use change by 2090s (Yang *et al*., 2003), although management practices may mitigate the sediment yield at catchment scale.

3.4.9. Extreme Hydrological Events (Floods and Droughts)

The SREX report (IPCC, 2012) recognized that projected precipitation and temperature changes imply possible changes in floods, although overall there is *low confidence* in projections of changes in fluvial floods. Projected increases in heavy rainfall would contribute to increases in rain generating local flooding, in some catchments or regions (Kundzewicz, 2013; Seneviratne *et al*., 2012). The studies supporting these assessments relied on a single GCM, which was the major source of *limited evidence* and thus *low confidence* in SREX (IPCC, 2012). Recent literature on global flood projections are based on ensemble from global hydrology models couple with multiple CMIP5 GCM simulations (Dankers *et al*., 2013; Hirabayashi *et al*., 2013). These model experiments show that flood hazards are increasing in more than half of the globe with a great variability even at the scale of individual river basins. In general, these studies show consistent results with increasing flood hazards occurring in parts of South Asia, Southeast Asia, East Africa, Central and West Africa, Northeast Eurasia, and South America. In contrast, a decrease in flood frequency was projected in parts of North and East Europe, Anatolia, Central Asia, central North America, and southern South America (Figure 3-8). This overall pattern is considerably similar to what was described in SREX (IPCC, 2012) as a summary of limited global or continental scale studies where each study relied on a single or a limited number of climate models. Thus, the global/continental-scale flood projection has gained ground and confidence could become higher than SREX (IPCC, 2012). However, uncertainty is still large at the global and continental scales particularly about the magnitude of changes. At local scale, even the sign of the change do not necessarily agree among GCMs (Dankers *et al*., 2013; Hirabayashi *et al*., 2013).

[INSERT FIGURE 3-8 HERE
Figure 3-8: Results of flood hazard change for the 30-year return level of river flow (Q30) from ensemble of 5 CMIP5 GCM simulations under RCP8.5 coupled with nine global hydrology and land surface models (named as impact models (IMs)) that provided simulations of daily river discharge at a global 0.5-degree grid for two 30-year periods (1971-2000 and 2070-2090) (Dankers *et al*., 2013). Top: Number of experiments (out of 45 in total) showing an increase (top left) or decrease (top right) in the magnitude of Q30 of more than 10% in 2070-2099 under RCP8.5, compared to 1971-2000. Bottom left: Average change in the magnitude of Q30 across all experiments.

Bottom right: Ratio of GCM variance to IM variance. GCM variance was computed as the variance of the change in Q30 across all GCMs for each individual IM, and then averaged over the 9 IMs; IM variance was computed as the variance of the change in Q30 across all IMs for each individual GCM, and then averaged over the 9 GCMs. In dark green (purple) areas GCM (IM) variance predominates.]

Projections at the catchment and/or river-basin scale are also being carried out (e.g, Dobler *et al*., 2012; Kay and Jones, 2012; Rojas *et al*., 2012) in addition to examples referred to in SREX (IPCC, 2012) and AR4, although projections for developing countries and regions are still limited (e.g., Ghosh and Dutta, 2012; Hunukumbura and Tachikawa 2012; Khazaei *et al*., 2012) and they tend to rely on a single or a limited number of climate models.

SREX (IPCC, 2012) assessed the projection of drought as: There is *medium confidence* in a projected increase in duration and intensity of droughts in some regions of the world, including southern Europe and the Mediterranean region, central Europe, central North America, Central America and Mexico, northeast Brazil, and southern Africa. Elsewhere there is overall *low confidence* because of insufficient agreement of projections of drought changes (dependent both on model and dryness index). Definitional issues and lack of data preclude *higher confidence* than *medium* in observations of drought changes, while these issues plus the inability of models to include all the factors *likely* to influence droughts preclude stronger *confidence* than *medium* in the projections. Note that the assessment of SREX (IPCC, 2012) is different to a certain degree from the one in AR4, in that confidence has become slightly lower, after carefully re-examining the AR4 assessment and adding post-AR4 studies.

Recently future changes in consecutive dry days (CDD) and simulated soil moisture anomalies (SMA) are calculated based on CMIP5 multi-model outputs, and compared CMIP5-based drought projections with CMIP3-based projections that were shown in SREX (Orlowsky and Seneviratne, 2012). It turns out that CMIP5-based projections are generally consistent with CMIP3-based projections except that drought at northeast Brazil is not clear by the SMA index obtained from CMIP5. Therefore, the above assessment on global-scale drought projection in SREX (IPCC, 2012) could remain almost the same here, even though definitional issues of drought remain yet to be solved.

3.5. Impacts, Vulnerabilities, and Risks

3.5.1. Availability of Water Resources

Approximately 80% of the world's population is currently exposed to high levels of threat to water security, in terms of a range of indicators including water availability , water demand and pollution (Vörösmarty *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 Vörösmarty *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*., 2011c; Arnell *et al*., 2013b; Fung *et al*., 2011; Gosling and Arnell, 2013; Hayashi *et al*., 2010; Schewe *et al*., 2013), whilst others have projected future human withdrawals and characterized availability by the ratio of withdrawals to runoff or recharge availability (Arnell *et al*., 2011c; Gosling and Arnell, 2013). Döll (2009) constructed a groundwater sensitivity index which combined water availability with dependence on groundwater and the Human Development Index (Figure 3-9). In a study with five climate models driving eleven global hydrological models, climate change was estimated to add, on average, about 40% to the global number of people living under extreme water shortage, for a global mean temperature rise of 2.7°C above pre-industrial (Schewe *et al*., 2013). Up to this temperature rise, each degree of global warming is projected to confront an additional 7% of the global population with a severe decrease in water resources of 20% (Schewe *et al*., 2013; Table 3-2). 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 (Arnell *et al*., 2011c; Döll, 2009; Portmann *et al*., 2013; Schewe *et al*., 2013). 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, some water-stressed areas see increased runoff in the future (Section 3.4.5), and therefore a reduction in exposure to water resources stress -varying with the spatial pattern of projected changes in rainfall. Third, over the next few decades and for increases in global mean temperature of less than around 2ºC above pre-industrial, changes in population will generally have a greater effect on changes in resource availability, relative to the present day, than climate change (Fung *et al*., 2011). Climate change would, however, regionally exacerbate or offset population pressures. Fourth, estimates of future water availability are sensitive not only to projections of future climate change and population assumptions, but also to hydrological impact model (Schewe *et al*., 2013) and the specific measure of stress or scarcity used.

[INSERT FIGURE 3-9 HERE
Figure 3-9: Human vulnerability to climate change induced decreases of renewable groundwater resources by the 2050s for four climate change scenarios in which lower (B2) and higher (A2) emissions pathways are interpreted by two global climate models. 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).]

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). The percentage of projected global population (SSP2 population scenario) that will suffer from a decrease of renewable groundwater resources GWR of more than 10% by the 2080s as compared to 1971-2000 was computed to range from 24% (mean based on 5 GCMs, range 11-39%) for RCP2.6 to 38% (range 27-50%) for RCP8.5 (Portmann *et al*., 2013; Table 3-2). Considering change of GWR as a function of mean global temperature (GMT) rise, the land areas affected by GWR decreases of more than 30% and 70% increase linearly with GMT between 0°C and 3°C. For each degree of GMT rise, an additional 4% of the global land area is cprojected to suffer from a GWR decrease of more than 30%, and an additional 1% to s a decrease of more than 70% (Portmann *et al*., 2013).

3.5.2. Water Uses

3.5.2.1. Agriculture

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). Crop transpiration and therefore irrigation water requirements are *likely* affected by physiological and structural crop responses to increased atmospheric CO_2 concentration (Box CC-VW). Using 19 climate models to drive a global vegetation and hydrology, it was projected that global irrigation water requirement on areas presently equipped for irrigation would decrease by on average by 17% by the 2080s (if not limited by poor soils and nutrient availability), while it would remain approximately constant if CO_2 effects were not taken into account (Konzmann *et al*., 2013). Even with the maximum CO_2-effect, increases of more than 20% are projected for Southern Europe and parts of China, the USA, Russia and Chile (Box CC-VW).

Irrigating crops can influence regional climate considerable. Irrigation is used to produce over 40% of the world's food, this is why irrigation is a one of the key elemements for food security in the future.

Effects of global irrigation on the near surface climate
It has been found (Sacks *et al*., 2009) that irrigation alters climate for instance by indirect effects like an increase in cloud cover. This effect can be significant in some regions, for example: cooling central and southern US, China,

and parts of Asia, in contrast, it warmed Canada by about 1 C°. Nevertheless, the impact is only at a regional level, as agriculture has little impact on the global mean temperatures. Precipitation increase occurs primarily downwind of the major irrigation areas, although precipitation in part of India decreases due to weaker summer (Puma and Cook, 2010).

Irrigation as adaptation strategy

Farmers could optimize production by adapting their use of fertilizers, pesticides and irrigation water to change climatic, political and economic conditions. To manage increasing yield variability and potential decrease in yield levels, irrigation constitutes an additional adaptation option which farmers might use (Finger *et al*., 2011).

About 4% of Sub-Saharan Africa arable land is irrigated. Irrigated land yields are up to five times that of rain fed areas. However, it must be the case that the costs of irrigation (e.g., capital, administrative, political) are high enough to balance or offset the benefits, thus and evaluation should be made considering local conditions (World Bank, 2009).

A study quantifying global changes in irrigation requirements on areas presently equipped for irrigation of major crop types has been realized indicating results from 19 GCMs for the year 2080. It was found a decrease in global irrigation of about 17% in the ensemble median. Additionally, an increase of more than 20% is projected with (*high likelihood*) for some regions such as South Europe and (*lower likelihood*) in Asia and North America.

Shifts in sowing dates constitute an adaptation option, for insance for maize production in Switzerland (World Bank, 2009), but sometimes this have to be combined with irrigation (Meza *et al*., 2009).

Complementary between mitigation and adaptation

A comparison of optimal input levels of nitrogen between rainfed and irrigated farming system shows different adaptation strategies. In rainfed production systems, reduced summer rainfalls lead to a reduction of the optimal production intensity for current and future scenarios. On the contrary, an increased application of nitrogen (i.e., a more intensive production) is an optimal response to climate change if irrigation is available. The difference in yield levels and yield variability between irrigated and rainfed farming systems will be higher with more marked climatic conditions (Finger *et al*., 2011).

3.5.2.2. Energy Production

Large amounts of water are required to produce energy by thermal power plants, hydropower and irrigated bioenergy crops (see Box CC-WE). Therefore, hydrological changes (Section 3.4) are expected to affect energy production, while changes in energy production due to climate change mitigation efforts will alter freshwater systems (Section 3.7.2.1), e.g. water availability for freshwater ecosystems (Section 3.5.2.4).

Hydropower generation is affected by changes in the mean annual river discharge, seasonal flows and daily flow variability as well as increased evaporation from reservoirs and changes in sediment fluxes. Projections of future hydropower generation in the Pacific Northwest of the USA are uncertain mainly due to the uncertainty of projected precipitation (Markoff and Cullen, 2008). Hydropower generation of Lake Nasser (Egypt) was computed to remain constant until the 2050s (based on an ensemble of 11 GCMs) but to decrease, on average (ensemble mean), to 90% of current mean annual production for the A2 (B1) emissions scenario, following the downward trend of mean annual river discharge (Beyene *et al*., 2010; Table 3-2). In snow-dominated basins, increased discharge in winter and lower and earlier spring floods have already been observed (Section 3.2.5) and the trend is *very likely* to continue in the future. 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 costed effective (Madani and Lund, 2010).

Regarding water availability for cooling of thermal power plants, the number of days with a reduced useable capacity is projected to increase in Europe and the USA, caused by increased stream temperatures and occurrence of low flows (van Vliet *et al*., 2012; Flörke *et al*., 2012). Lower emissions also lead to less severe impacts of climate change (Table 3-2). Economic implications of the impact of climate change on thermal power and hydropower production as well as adaptation options are discussed in Chapter 10.

3.5.2.3. Municipal Services

Under anthropogenically altered climate conditions, water utilities are confronted by the following (Bates *et al*., 2008; Black and King, 2009; Bonte and Zwolsman, 2010; Brooks *et al*., 2009; Chakraborti *et al*., 2011; Christierson *et al*., 2012; Hall and Murphy, 2010; Jiménez, 2008a; Major *et al*., 2011; Mukhopadhyay and Dutta, 2010; Qin *et al*., 2010; Thorne and Fenner, 2011b; van Vliet and Zwolsman, 2008; Whitehead *et al*., 2009):

- Higher ambient temperatures is very likely to reduce snowpacks and glaciers, also they are very likely to increase the evaporation rate in lakes, reservoirs and aquifers. Both impacts is very likely to reduce the amount of water naturally stored reducing its availability. At the same time higher ambient temperatures is likely to increase the demand for municipal water as for many other uses. The overall situation resulting in a higher competition for water from different users.
- Shifts in river flows and the occurrence of droughts are likely to increase the need for artificial storage capacity.
- Higher water temperatures which exacerbate algal blooms in surface water potentially demanding for cyanotoxins control. Also a warmer environment potentially leads to changes in the quantity and quality of natural organic matter in water sources that are at the origin of disinfection by-products in chlorinated water. These issues contrast with potential increases in the efficiency of biological water and wastewater treatement processes resulting from increased water temperatures (Tchobanoglous *et al*., 2003).
- Drier conditions, resulting in a higher concentration of pollutants due to a reduction in dilution capacity. For groundwater sources, some pollutants of natural origin, including arsenic, iron, manganese and flurorides are likely to be an additional source of concern in areas already affected from, South East Asia (India), North and Latin America and Africa (Black and King, 2009).
- Elevated storm runoff, leading to higher loads of pathogens, nutrients and turbidity in water bodies from point and non-point sources of pollution. The indicators traditionally used to assess faecal pollution (faecal bacteria), as a result, is likely to be insufficient to track pathogens.
- Sea level rise, leading to increased salinity in aquifers in particular where groundwater recharge is very likely to decrease.

Water supply

With respect to the safe supply of water, many treatment plants are not designed to handle extreme influent variations that occur under climate variable conditions. These demand additional or even different infrastructure for treatment during periods of one to up to several months per year. In order merely to control the increased turbidity that would be *likely* to interfer with the disinfection process, higher coagulant doses would be needed, greater volumes of sludge would then be produced and need to be disposed increasing treatment costs (Zwolsman *et al*., 2010; Arnel *et al*., 2011). Depending on the extent of the impacts and local conditions resulting costs may or not be affordable.

Sanitation service

With regard to sewers, three climatic conditions are of interest from the perspectives of design and operation (NACWA, 2009; Zwolsman *et al*., 2010):

- Wet weather conditions -Heavy rainstorms challenge the existing capacity of sewerage systems due to the need to deal with increased amounts of pluvial water and even wastewater in combined systems, even for short periods of time. The current design, based on critical “design storms” defined through analysis of historical precipitation data, must be modified to include future scenarios. In addition new strategies to

prevent urban floods have to be developed considering not only the future climate but also many other factors such as urban design, land use, the "heat island effect" and topography (Chagnon, 1969).
- Sea level rise -The intrusion of brackish or salty water to sewers necessitates not only additional capacity of wastewater treatment but also processes that are able to operate with more saline wastewater.
- Dry weather conditions -During dry conditions, soil shrink as they lose humidity, eventually causing the cracking of water mains and sewers and with this the infiltration and exfiltration of water/wastewater. The combined effects of higher temperatures, increased concentrations of pollutants, longer retention times, and solids sedimentation may lead to increasing corrosion of sewers, shortening asset life and increasing maintenance costs. This is also likely to cause problems of septicity, higher pollutant contents and increased "first flush" concentrations.

Cities suffering from increased storm runoff are likely to experience the need to treat combined sewer overflows (CSO), due to increased amounts and varieties of pathogens and pollutants. Under drier conditions a high content of pollutants in wastewater, of any type, is to be expected and has to be dealt with (Whitehead *et al*., 2009a; 2009b; Zwolsman *et al*., 2010). This is unlikely to be feasible in low income regions (Chakraborti *et al*., 2011; Jiménez, 2011). 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 low income countries is discharged untreated into water bodies or to the ground (UNICEF-WHO, 2012; WWAP, 2009). In addition, the disposal of wastewater or faecal sludge is a concern that is just beginning to be studied (*low to medium confidence, limited evidence*) (Seidu *et al*., 2013).

3.5.2.4. 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 (discussed in Chapter 4) but also by altered flow regimes, water levels and extent and timing of inundation (Box CC-RF).

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).

In addition, climate change leads to water quality changes (Section 3.2.5) 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 biota (Ficke *et al*., 2007).

3.5.2.5. Other Uses

In addition to the direct impacts, vulnerabilities, and risks in the water-related sectors, indirect impacts from changes in the hydrological systems are expected in sectors, such as navigation, transportation, tourism, and urban planning (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 is *likely* to increase the risks of violent conflicts and nation-state instability (Barnett and Adger, 2007; Buhaug *et al*., 2010; Burke *et al*. 2009; Hsiang *et al*., 2011).

As a consequence of snowline rising and glacier vanishing, damage on environmental, hydrological, geomorphological, heritage, and tourism resources is *very likely* 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).

3.5.3. Impact Costs of Extreme Events

Reported flood damages (adjusted to inflation) have increased over the period 1980-2011 from an average of 7 billion US$ per year in the 1980s to about 24 billion US$ per year of which an average of 9% was insured (data from Munich Re, 2012). The SREX report (IPCC, 2012) indicated that economic, including insured, flood disaster losses are higher in developed countries, while fatality rates and economic losses expressed as a proportion of gross domestic product (GDP) are higher in developing countries (Handmer *et al*., 2012). Currently about 800 million people worldwide (i.e. over 11% of global population) are living in flood-prone areas, and about 70 million of those people (i.e. 1% of global population) are, on average, exposed to floods each year (UNISDR, 2011). The population living in flood-prone areas has increased faster than overall population or economic growth (Bouwer *et al*., 2007; Bouwer, 2011; Jongman *et al*., 2012), in part explaining the observed increase in flood damage. Average number of deaths since 1980 is on the order of thousands casualties per year, of which over 95% of deaths occurred in developing countries, with the highest number (75%) are concentrated in southern, south-eastern and eastern Asia (Handmer *et al*., 2012). The loss of life has been decreased considerably, particularly in high income areas, due to improved flood protection and management measures (UNISDR, 2011). One of most vulnerable countries in the Asian region is Pakistan that has been affected by three consecutive years of flooding with nearly 2000 deaths in 2010, followed by 2011 and 2012 which flooding caused at least 360 and 480 deaths respectively.

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; 2009; Jiang *et al*., 2005; Miller *et al*., 2008). 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 loss data, and to the high 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 in the analysis of impacts as there are not systematically reported or documented on national or global databases. These local weather extremes have increased their direct damage costs to society increasing the statistics on the number of flood disaster, in the sense that even small floods has a potential to cause catastrophic impacts.

Water related impacts (floods and droughts) are projected to increase even in case of constant hazard due to the increase in the population exposed and vulnerability (Kundzewicz, 2013). At global scale, there is a marked regional variability (largest losses in Asia), and a wide range of results between climate models. For instance, analysis from 21 climate models under SRES A1b shows that population exposed by 2050 to a doubling flood frequency range from 31 to 449 million people, and the change in risk varies between -9 and +376% (Arnell and Gosling, 2013a). Detail studies estimating future expected economic losses are mainly focussed in Europe, USA and Australia (Handmer *et al*., 2012; Bouwer *et al*., 2012). In the case of Europe (Feyen *et al*., 2012), the current (control period: 1961-1990) €6.4 billion per year annual damage and 200,000 annual population exposed is expected to increase about twice under scenario B2 (€14-15 billion per year and 440.000-470.000 annual people exposed) and about three times under scenario A2 (€18-21 billion per year and with annual population exposed of 510,000-590,000). According to Handmer *et al*. (2012), the main driver for future increasing losses of water relates disasters in developing countries will be socioeconomic in nature as result of changes in population and exposure of people and assets (based on *medium agreement* and *limited evidence*), with effects of climate change amplifying the impacts of expected losses

The costs of inland waterway transport is *likely* to increase due to increased frequency of low water levels, as e.g. was shown in the impositions of ship draft restrictions during the El Niño 1996. Most direct impacts and costs are still uncertain and ambiguous (Koetse and Rietveld, 2009). On the other hand, extreme high water levels in rivers is *likely* to increasing sedimentation of navigation channels and hence cause higher costs for navigation due to more necessary channel dredging (Pinter *et al*., 2006).

3.6. Adaptation and Managing Risks

In the face of impacts on water resources, floods and droughts and the changes in water use because of climate change, there is need for adaptation and to increase resilience. Moreover, even to take advantages of possible positive impacts there is need for adaptation. Managing the changing risks due to the impacts of climate change is the key in the adaptation in water sectors (IPCC, 2012), and risk management should be part of decision making and used to deal with uncertainty (ISO 31000, Risk Management (ISO, 2009)). In the next sections, in a generic way, adaptation options are discussed, followed by some reflections on the limits for adaptation and its costs. The need to build capacity in this area is also discussed.

3.6.1. Adaptation Options

Since the 3rd IPCC assessment report efforts have been made to identify options for adaptation in the water sector. Many of them are or were applied simply as a response to climate variability and not directly climate change. Climate change provides many opportunities for improvements as "no regret" actions, which are actions able to generate net social and/or economic benefits can be implemented to address both climate variability and climate change. Table 3-3 present different categories of adaptation options reported in the literature.

[INSERT TABLE 3-3 HERE
Table 3-3: Categories of climate change adaptation measures regarding to freshwater.
CC: Particular relevant to climate change, M+A: assist both mitigation and adaptation, M: also assist mitigation]

Adaptation measures, which involve a combination of 'hard' infrastructural and 'soft' institutional actions, can be helpful in reducing vulnerability. Individual regional measures can be identified by 'climate proofing' and implemented as various actions, such as implementing low-regret flood-risk management programs and conduct capacity building (Bates *et al*., 2008; Cooley, 2008; Mertz *et al*., 2009; Olhoff and Schaer, 2010; Sadoff and Muller, 2009; UNECE, 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 increases the capacity to cope with projected risks or where the investment is justified under all plausible future scenarios, might be aspired (World Bank, 2007). One option to obviate maladaptation is to identify and evaluate the use of virtual water in the countries receiving commodities, and to include externalities in the pricing of exports.

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) for introducing environmental considerations into IWRM. IWRM is an internationally accepted approach for efficient, equitable and sustainable development and management of water resources and water demands to ensure productive and healthy ecosystems by integrating social, economic, physical, and biological needs and values (GEF-ADB, 2006). In parallel to the implementation of the IWRM approach there is an increase in the attention to adaptive management and robust measures (European Communities, 2009). A robust measure can be defined as a measure that performs well under different future conditions and clearly optimizes prevailing strategies (Sigel *et al.*, 2010).

Past experience suggests that adaptations are best achieved through mainstreaming and integrating climate responses into sustainable development and poverty eradication processes, rather than by identifying and treating them separately (Elasha, 2008). 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 and planning processes in light of climate change and uncertainty in future hydrological conditions are well discussed (Bates *et al*., 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.

3.6.2 Limits to Adaptation

Limits to Adaptation are discussed in detail in Chapter 16 (Section 16.5). Here, barriers to adaptations referring to freshwater resources are highlighted (Burton, 2008). Barriers such as lack of technical capacity, financial resources, awareness, communication etc., are relevant to freshwater resources management. Some of the barriers that are of importance besides technical aspects are the social and economic ones, such as (Butscher and Huggenberger, 2009; Zwolsman *et al*., 2010; 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.

3.6.3 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 3.6.6) is their treatment of uncertainty.

Some approaches (e.g. in England and Wales; Arnell, 2011a) use a small set of climate scenarios to characterise the potential range in impacts. Much attention, however, has been directed towards methods which use very large numbers of scenarios to produce ‘likelihood distributions’ of indicators of impact (e.g., Brekke *et al*., 2008; Christierson *et al*., 2012; Hall *et al*., 2012; Lopez *et al*., 2009) for use in risk assessment. 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 (Dessai *et al*., 2009; Hall, 2007; Stainforth *et al*., 2007) 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) and others therefore argue that it is impossible for practical purposes to construct robust quantitative probability distributions of climate change impacts, and climate change uncertainty needs to be represented differently, for example through the use of a smaller number of plausible scenarios and the less literal interpretation of scenario results.

A section of the literature goes further, arguing that climate models are not sufficiently robust or reliable to provide any basis for adaptation (Anagnostopoulos *et al*., 2010; Blöschl and Montanari, 2010; Koutsoyiannis *et al*., 2008; Lins and Cohn, 2011; Stakhiv, 2011; Wilby, 2010). It is argued that current climate models are frequently biased, and do not reproduce the temporal characteristics -specifically persistence- often found in hydrological records. Existing water resources planning methods, which incorporate uncertainty stochastically and can take persistence into account, are therefore sufficient to address the effects of climate change (Lins and Cohn, 2011; Stakhiv, 2011). This view of climate model performance has been challenged and is the subject of some debate (Huard, 2011;

Koutsoyiannis *et al*., 2011); the critique also assumes that adaptation assessment procedures would only use climate scenarios derived directly from climate model simulations.

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*) (e.g. Matthews and Wickel, 2009). An example of this approach is provided by Henriques and 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; Nassoploulos *et al*., 2012) is a more formalised way of constructing robust and resilient adaptation strategies, and combines features of classic decision analysis and traditional scenario planning. The first stage assesses the performance of a set of defined adaptation actions against a wide range of plausible future conditions. This is similar to traditional scenario planning, but there are two main differences. First, the focus 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. This approach was applied to the Inland Empire Utilities Agency, supplying water to a region in southern California (Lempert and Groves, 2010). 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.

3.6.4. Capacity Building

Strengthening the professional capacity and communication on climate change adaptation is essential to cope with the increasing vulnerability to climate change. Capacity building in the water sector means to acquire relevant hydrological and climate information, to make use of this information in water 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 in the water sector, 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 so they will understand the use and methodology of appropriate technologies (Bates *et al*., 2008; Halsnæs and Trærup, 2009; Olhoff and Schaer, 2010; Smit and Wandel, 2006; UNECE, 2009; von Storch, 2009).

Finally, the capacity of water management agencies and the water management system as a whole is *likely* to 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 (Crabbe and Robin, 2006; Ivey *et al*., 2004; Næss *et al*., 2005; Parry *et al*., 2007).

3.6.5. Costs of Adaptation to Climate Change

Considering the importance of adapting to climate change in the water sector, the literature on this topic is relatively 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, 2006).

At the local, national, and river basin level, the geographical distribution of these researches is skewed towards developed countries, although examples do exist in developing countries. Adapting urban water infrastructure in sub-Saharan Africa to climate change is estimated to be US$25 billion per year (Muller, 2007). 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.

The global costs of adaptation in water resources associated with additional water infrastructure needed.have been assessed (Kirshen, 2007; UNFCCC, 2007; Ward *et al*., 2010). To provide a sufficient water supply, the adaptation costs were estimated to amount to ca. US$531 billion in total for the period up to 2030 given present and future projected water demands and supplies in more than 200 countries (Kirshen, 2007). Of this, US$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. US$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. US$225 billion up to 2030. This is equivalent to ca. US$11 billion/year (UNFCCC, 2007).

3.6.6. Case Studies

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 Connell-Buck *et al*. (2011) and Medellin-Azuara *et al*. (2008) in California, Miles *et al*. (2010) in Washington State USA, Pittock and Finlayson (2011) in the Murray-Darling basin in Australia, and Hoekstra and de Kok (2008) on dike heightening in the Netherlands). The second group presents methodologies for assessing the impacts of climate change specifically for adaptation purposes. For example, Brekke *et al*. (2008; 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 (Gersonius *et al*., 2013; Huntjens *et al*., 2012; Mysiak *et al*., 2009; Pahl-Wostl, 2007; Pahl-Wostl *et al*., 2008; Short *et al*., 2012) and the adoption of ‘resilient’ or ‘no-regrets’ approaches (Henriques and Spraggs, 2011; WWAP, 2009). 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 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 3.6.3). 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 (Bergsma *et al*., 2012; Engle and Lemos, 2010; Goulden *et al*., 2009; Huntjens *et al*., 2010; Stuart-Hill and Schulze, 2010; Wilby and Vaughan, 2011; Ziervogel *et al*., 2010). 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 a considerably smaller literature describing what water management agencies are actually currently doing to adapt to climate change. 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 (e.g. Rudberg *et al*., 2012), and therefore represents attempts to improve adaptive capacity. 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 (2011b) describing the evolution of methodologies for water resources assessment under climate change in England and Wales). Several studies report community level activities to reduce exposure to current hydrological variability as a means of adapting to future climate change (e.g. Barrios *et al*., 2009; Gujja *et al*., 2009; Kashaigili *et al*., 2009; Yu *et al*., 2009).

3.7. Linkages with Other Sectors and Services

3.7.1. Impacts of Adaptation in Other Sectors on Freshwater Systems

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, while allowing controlled flooding of agricultural land can alleviate flooding in urban areas. 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 can affect GHG emissions (Bates *et al*., 2008).

3.7.2.1. Impact of Climate Change Mitigation in Different Sectors on Freshwater Systems

Afforestation of areas suitable according to the Clean Development Mechanism-Afforestation/Reforestation provisions of the Kyoto Protocol (7.5 million km^2) would lead to high and large-scale decreases of long-term average runoff (Trabucco *et al*., 2008). On 80% of the area, runoff is computed to decline by more than 40%, while on 27% runoff decreases by 80-100% were computed, mostly in semi-arid areas (Trabucco *et al*., 2008). For example, 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 is viable to the forestry industry under current water tariffs and current carbon accounting legislation, but would be unviable if the forestry industry were to pay the true cost of water used by the plantations (Chisholm, 2010). Depending on local conditions, runoff decreases is likely to have beneficial impacts, e.g. on soil erosion, flood risk, water quality (nitrogen, phosphorus, suspended sediments) and stream habitat quality (Trabucco *et al*., 2008; Wilcock *et al*., 2008).

Renewable energy production in the form of irrigated bioenergy crop production and hydropower generation has negative impacts on freshwater systems (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 m^3 consumptive water use per 1 m^3 of ethanol (King *et al*., 2010). In two scenarios, this fraction increases to 9% in 2030, with future water consumption strongly depending on the degree of irrigation (King *et al*., 2010). Also biofuel crops like switchgrass and 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 meter that energy gain by higher crop yields under irrigation is lower than the energy consumption for pumping (Gupta *et al*., 2010). For a biofuel production scenario of the International Energy Agency, global consumptive irrigation water use for biofuel production is projected to increase from 0.5% of global renewable water resources in 2005 to 5.5% in 2030; in some countries biofuel production is likely to lead to a significant percent increase of water consumption (e.g. Germany, Italy and South Africa), while in others it exacerbates a already high water scarcity (e.g. Spain and China) (Gerbens-Leenes *et al*., 2012). Conversion of native Caatinga forest into rainfed 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. 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).

CO_2 leakage from saline aquifers used for Carbon Capture and Storage (CCS) to freshwater aquifers is very likely to lead to a pH decline of 1-2 units and increased concentrations of metals, 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). Densification of urban areas to reduce traffic emissions is likely to 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 wastewater. Water supply and treatment consumes approximately 1.4 % of total electricity consumption in Japan in Japanese Fiscal Year 2008 (MLIT, 2011). 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 wastewater 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 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 Southeast Asia is very likely to lead to substantial reductions of net GHG emissions (Couwenberg *et al*., 2010). Climate change mitigation by 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 emissions. 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 be decreased by 4.1 Tg/a (15%), and no significant increase in N_2O emissions would occur (Yan *et al*., 2009).

3.8. 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 available groundwater resources, 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, arterial drainage, long-range diversion, 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.

Modeling studies have shown that the adaptation of vegetation to changing climate may have large impacts on the partitioning of precipitation into evapotranspiration and runoff. This feedback should be investigated more thoroughly.

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 and global climate models, or improving the accuracy of methods for downscaling their outputs, can produce information of more relevance to water management, although robustness of regional climate projections is still constrained by the realism of GCM simulations of large-scale drivers. 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. Robust attribution to anthropogenic climate change of hydrological changes, particularly changes in the frequency of extreme events, is similarly demanding, and further study is required to develop rigorous attribution tools that require less computation.

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.

To allow adaptation to climate change by increased reliance of water supply on groundwater and on the coordinated and combined use of ground water and surface water, the following research and data gaps have to be closed:

- Ground-based data on groundwater dynamics and stored groundwater volumes
- A long-term monitoring program for evaluation of the response of groundwater to climate change
- Better understanding of groundwater recharge and groundwater-surface water interactions
- Assessment of experiences of conjunctive use of groundwater and surface water, including managed aquifer recharge

More studies are needed, notably in developing countries, of the impacts of climate change on water quality, and of vulnerability to and ways of adapting to those impacts.

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 renewable water resources at the regional scale, although sometimes with large uncertainty. Evapotranspiration is very likely to increase over land. 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 changes in seasonal flow regime due ot decreases in snow and ice storage, groundwater recharge, degradation of water quality, and more variable streamflow due to more variable precipitation.

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

Projected climate change will change the frequency and magnitude of floods, although the amount and sign of change will vary across the globe. There is considerable uncertainty in the magnitude of regional-scale change due to disagreement between simulations of precipitation. Recent modeling of flood hazards suggests that they will increase over more than half of the globe. More frequent intense rainfall (WG1 SOD 12.4.5.5) would increase the frequency of flooding in small catchments, but the limited extent of intense rainfall events makes the implications more uncertain for larger catchments. The magnitude of spring snowmelt floods is likely to decrease, because less precipitation will fall as snow during winter. The few available studies show strong consistency in projecting increases in flood hazards over central and eastern Siberia, parts of south-east Asia including India, East Africa, Central and West Africa, and northern South America, and decreases in flood hazards in parts of North and East Europe, Anatolia, Central-East Asia, central North America, and southern South America.

Flood hazards will increase flood damages worldwide, enhanced by increasing exposure, particularly on flood-prone valley floors and deltas, of people and assets. Flood disasters may be triggered by weather events that are not statistically extreme but are hazardous because of social conditions that increase exposure and vulnerability. Flood losses in many locations will increase in the absence of additional protection measures, but the increase varies strongly with location, climate model, and the method used to assess exposure and vulnerability.

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

It depends. Impacts of climatic changes on freshwater are different in character from those of other stressors such as land-use change, water withdrawal, artificial drainage of wetlands, dam construction, alteration of river morphology, and water pollution. Climatic changes, such as changes in the amount and intensity of precipitation, are global in scope and affect all compartments of the freshwater system (soil, groundwater, lakes, wetlands and watercourses). The relative seriousness of climate-related stress varies depending on the region, the freshwater compartment and the type of stress. For example no other human stress, apart perhaps from deforestation, could have an impact comparable to that of increased flooding due to more intense rainfall. On the other hand, irrigated agriculture has already led, in some semi-arid regions, to streamflow reductions comparable to or worse than those expected from climatic changes. Finally, the answer depends on the time horizon and on the success of climate-change mitigation. Global population is expected to peak in the mid-21st century, while climatic changes may not peak until much later. The impacts of climate change will therefore become progressively more serious relative to those of other human impacts.

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

Water-resource management under uncertain climate change needs to be approached as a part of natural-resource management, integrated with suitable social measures and development of infrastructure. Restoring and protecting freshwater habitats, and managing natural floodplains, are key elements of such an approach. Adaptive measures that may prove particularly effective include rainwater harvesting, conservation tillage, maintaining vegetation cover, planting trees in steeply-sloping fields, mini-terracing for soil and moisture conservation, improved pasture management, water re-use, desalination, and more efficient soil and irrigation-water management. Possible examples of maladaptive measures include large projects, such as dams and irrigation systems, that fail to offer complete flood protection and that harm the adaptive capacity of other sectors; and unreasonably resource-intensive desalination, pumping of deep groundwater, or water treatment.

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 necessarily in the same places. Regions with abundant water at present may have yet more, but regions with deficits may suffer more serious shortages. These changes are already well attested globally, but in most regions it will be some decades before they become statistically detectable. Where water stress is alleviated by glacier meltwater there will be a “meltwater dividend” during the 21st century, although the total yield of meltwater will eventually diminish. Many of the adverse impacts of changes in water resources will be felt in the developing world, where investment in more careful management can be expected to be very cost-effective, for example by improving seasonal availability of water, under climate change.

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

A portfolio is a set of measures, defined locally, that are considered promising for adaptation to possible future climates and their variability. The measures can be implemented progressively and flexibly, in a coordinated and complementary way, and can be expected to reduce vulnerability and increase resilience. No-regrets measures are those that will yield benefits regardless of how the climate evolves; they are to be preferred. Providing universal access to safe water is an example of a no-regrets option.

Cross-Chapter Boxes

Box CC-RF. Impact of Climate-Change on Freshwater Ecosystems due to Altered River Flow Regimes

[Petra Döll (Germany), Stuart E. Bunn (Australia)]

It is widely acknowledged that the flow regime is a primary determinant of the structure and function of rivers and their associated floodplain wetlands, and flow alteration is considered to be a serious and continuing threat to freshwater ecosystems (Bunn and Arthington, 2002; Poff and Zimmerman, 2010; Poff *et al.*, 2010). Most species distribution models do not consider the effect of changing flow regimes (i.e. changes to the frequency, magnitude, duration and/or timing of key flow parameters) or they use precipitation as proxy for river flow (Heino *et al.*, 2009).

There is growing evidence that climate change will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (Aldous *et al.*, 2011; Xenopoulos *et al.*, 2005). By the 2050s, climate change is projected to impact river flow characteristics like long-term average discharge, seasonality and statistical high flows (but not statistical low flows) more strongly than dam construction and water withdrawals have done up to the year 2000 (Figure RF-1; Döll and Zhang, 2010). For one climate scenario, 15% of the global land area may suffer, by the 2050s, 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 exacerbate the negative impacts of dams for freshwater ecosystems but 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 RF-1 HERE
Figure RF-1: Impact of climate change on the ecologically relevant river flow characteristics mean annual river flow and monthly low flow Q_{90} as compared to the impact of water withdrawals and dams on natural flows, as computed by a global water model (Döll and Zhang, 2010). Impact of climate change is the percent change of flow between 1961-1990 and 2041-2070 according to the emissions scenario A2 as implemented by the global climate model HadCM3. Impact of water withdrawals and reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002.]

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). The relatively stable habitats of groundwater-fed streams in snow-dominated or glacierized basins may be altered by reduced recharge by meltwater and as a result experience more variable (possibly intermittent) flows (Hannah *et al.*, 2007). A high-impact change of flow variability is a flow regime shift from intermittent to perennial or vice versa. It is projected that until the 2050s, river flow regime shifts may occur on 5-7% of the global land area, mainly in semi-arid areas (Döll and Müller Schmied, 2012; see Chapter 3, Table 3-2).

In Africa, one third of fish species and one fifth of the endemic fish species occur in eco-regions that may experience a change in discharge or runoff of more than 40% by the 2050s (Thieme *et al.*, 2010). 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).

Due to increased winter temperatures, freshwater ecosystems in basins with significant snow storage are affected by higher river flows in winter, earlier spring peak flows and possibly reduced summer low flows (chapter 3.2.3). Strongly increased winter peak flows may lead to a decline in salmonid populations in the Pacific Northwest of the USA of 20-40% by the 2050s (depending on the climate model) due to scouring of the streambed during egg incubation, the relatively pristine high-elevation areas being affected most (Battin *et al.*, 2007). Reductions in summer low flows will increase the competition for water between ecosystems and irrigation water users (Stewart *et al.*, 2005). Ensuring environmental flows through purchasing or leasing water rights and altering reservoir release patterns will be an important adaptation strategy (Palmer *et al.*, 2009).

Observations and models suggest that global warming impacts on glacier and snow-fed streams and rivers will pass through two contrasting phases (Burkett *et al.*, 2005; Vuille *et al.*, 2008; Jacobsen *et al.*, 2012). In the first phase, when river discharge is increased due to intensified melting, the overall diversity and abundance of species may increase. However, changes in water temperature and stream-flow may have negative impacts on narrow range endemics (Jacobsen *et al.*, 2012). In the second phase, when snowfields melt early and glaciers have shrunken to the point that late-summer stream flow is reduced, broad negative impacts are foreseen, with species diversity rapidly declining once a critical threshold of roughly 50% glacial cover is crossed (Figure RF-2).

[INSERT FIGURE RF-2 HERE
Figure RF-2: Accumulated loss of regional species richness (gamma diversity) as a function of glacial cover GCC. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%. Each data point represents a river site and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.]

River discharge also influences the response of river temperatures to increases of air temperature. Globally averaged, air temperature increases of 2°C, 4°C and 6°C are estimated to lead to increases of annual mean river temperatures of 1.3°C, 2.6°C and 3.8°, respectively (van Vliet *et al.*, 2011). Discharge decreases of 20% and 40% are computed to result in additional increases of river water temperature of 0.3° C and 0.8°C on average (van Vliet *et al.*, 2011). Therefore, where rivers will experience drought more frequently in the future, freshwater-dependent biota will suffer not only directly by changed flow conditions but also by drought-induced river temperature increases, as well as by related decreased oxygen and increased pollutant concentrations.

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Box CC-VW. Active Role of Vegetation in Altering Water Flows Under Climate Change

[Richard Betts (UK), Dieter Gerten (Germany), Petra Döll (Germany)]

Terrestrial vegetation dynamics, carbon and water cycles are closely coupled, for example by the simultaneous transpiration and CO_2 uptake through plant stomata in the process of photosynthesis, and by feedbacks of land cover and land use change on water cycling.Numerous experimental studies have demonstrated that elevated atmospheric CO_2 concentration leads to reduced opening of stomatal apertures, associated with a decrease in leaf-level transpiration (de Boer *et al.*, 2011; Reddy *et al.*, 2011). This physiological effect of CO_2 is associated with an increased intrinsic water use efficiency (iWUE) of plants, as less water is transpired per unit of carbon assimilated. Records of stable carbon isotopes in woody plants (Peñuelas *et al.*, 2011) corroborate this finding, suggesting an increase in iWUE of mature trees by 20.5% between the 1970s and 2000s. Increases since pre-industrial times have also been found for several forest sites (Andreu-Hayles *et al.*, 2011; Gagen *et al.*, 2011; Loader *et al.*, 2011; Nock *et al.*, 2011) and in a temperate semi-natural grassland (Koehler *et al.*, 2010), although in one boreal tree species iWUE ceased to increase after 1970 (Gagen *et al.*, 2011). However, the physiological CO_2 effect is accompanied by structural changes to C3 plants (including all tree species), i.e. increased biomass production, spatial encroachment and, thus, higher transpiration, as confirmed by Free Air CO_2 Enrichment (FACE) techniques (Leakey *et al.*, 2009).

There are conflicting views on whether the direct CO_2 effects on plants already have a significant influence on evapotranspiration and runoff at global scale. AR4 reported work by Gedney *et al.*, (2006) which suggested that physiological CO_2effects (lower transpiration) contributed to a supposed global increase in runoff seen in reconstructions by (Labat *et al.*, 2004). However, a more recent dataset (Dai *et al.*, 2009) showed different runoff trends in some areas. Detection of ecosystem influences on terrestrial water flows, hence, critically depends on the availability and quality of hydrometeorological observations (Haddeland *et al.*, 2011; Lorenz and Kunstmann, 2012).

A key influence on the significance of increased iWUE for large-scale transpiration is whether overall leaf area of primary vegetation has remained approximately constant (Gedney *et al.*, 2006) or has increased in some regions due to structural CO_2effects (as assumed in models by Piao *et al.*, 2007; Gerten *et al.*, 2008). While field-based results vary considerably between sites, tree ring studies suggest that tree growth did not increase globally since the 1970s in response to climate and CO_2change (Peñuelas *et al.*, 2011; Andreu-Hayles *et al.*, 2011). However, basal area measurements at over 200 plots across the tropics suggest that biomass and growth rates in intact tropical forests have increased in recent decades (Lewis *et al.*, 2009), which is also confirmed for 55 temperate forest plots, with a suspected contribution of CO_2 rise (McMahon *et al.*, 2010). The net impact of CO_2 on global-scale transpiration and runoff therefore remains poorly constrained.

Moreover, model results differ in terms of the importance of CO_2 effects for historical runoff relative to other drivers such as climate, land use change and irrigation water withdrawal. Other than Gedney *et al.*, (2006), Piao *et al.*, (2007) and Gerten *et al.*, (2008) found that CO_2 effects on global runoff were small relative to effects of precipitation, and that land use change (which often acts to decrease evapotranspiration and to increase runoff) was of second-most importance, as also supported by Sterling *et al.*, (2012) data and model analysis. By contrast, using a shorter time period and a smaller selection of river basins, Alkama *et al.*, 2011(2011) suggested that global effects of land use change on runoff have been negligible. Oliveira *et al.*, 2011(2011) furthermore point to the importance of changes in incident solar radiation and the mediating role of vegetation; their global simulations demonstrate, for example, that a higher diffuse radiation fraction during 1960–1990 increased evapotranspiration in the tropics by 3% due to increased photosynthesis from shaded leaves. Since the anthropogenic component of the precipitation and temperature contributions(i.e. of the radiative CO_2 effect) to runoff trends is not yet established, a full attribution of anthropogenic emissions of CO_2 (and other greenhouse gases)is still missing.

Analogously, there is uncertainty about how vegetation responses to future increases in CO_2 will modulate effects of climate change on the terrestrial water balance.21st-century continental- and basin-scale runoff is projected by some models to either increase more or decrease less when CO_2-induced increases in iWUE are included in addition to climate change (Betts *et al.*, 2007; Murray *et al.*, 2012), potentially reducing an increase in water stress due to rising population or climate change (Wiltshire *et al.*, submitted) – although other models project a smaller response (Cao *et al.*, 2009). Direct effects of CO_2 on plants have been modelled to increase future global runoff by 4–5% (Gerten *et al.*, 2008) up to 13% (Nugent and Matthews, 2012), depending on the assumed CO_2 trajectory and whether feedbacks of changes in vegetation structure and distribution to the climate are accounted for. The model analysis by Alkama *et al.*, (2010) suggests that although the physiological CO_2 effect will be the second-most important factor for 21st-centuryglobal runoff and although both physiological and structural effects will amplify compared to historic conditions, runoff changes will still primarily follow the projected climatic changes. Using a large ensemble of climate change projections, Konzmann *et al.*, (2013) put hydrological changes into an agricultural perspective and suggest that direct CO_2 effects on crops reduce their irrigation requirements (Fig. CC-VW-1). Thus, adverse climate change impacts on crop yields might be partly buffered as iWUE improves (Fader *et al.*, 2010), but only if proper management abates limitation of plant growth by nutrient availability or other factors. Lower transpiration under rising CO_2 may also affect future regional climate change itself (Boucher *et al.*, 2009) and may enhance the contrast between land and ocean surface warming (Joshi *et al.*, 2008).

Application of a soil-vegetation-atmosphere-transfer model indicates complex responses of groundwater recharge to changes in different climatic variables mediated by vegetation,with computed groundwater recharge being always larger than would be expected from just accounting for changes in rainfall (McCallum *et al.*, 2010). In a warmer climate with increased atmospheric CO_2 concentration, iWUE of plants increases and leaf area may either increase or decrease, and even though precipitation may slightly decrease, groundwater recharge may increase as a net effect of these interactions (Crosbie *et al.*, 2010). Depending on the type of grass in Australia, the same change in climate is suggested to lead to either increasing or decreasing groundwater recharge in this location (Green *et al.*, 2007). For a location in the Netherlands, a biomass decrease was computed for each of eight climate scenarios indicating drier summers and wetter winters (A2 emissions scenario), using a fully coupled vegetation and variably saturated hydrological model. The resulting increase in groundwater recharge up-slope was simulated to lead to higher water tables and an extended habitat for down-slope moisture-adapted vegetation (Brolsma *et al.*, 2010).

Future anthropogenic and climate-driven land cover and land use changes will also affect regional evapotranspiration, surface and subsurface water flows, with the direction and magnitude of these changes depending on the direction and intensity of the changes in vegetation coverage,as shown e.g. for a river basin in Iowa (Schilling *et al.*, 2008) or for the Elbe river basin (Conradt *et al.*, 2012).Removal of vegetation acting as source of atmospheric moisture can change regional water cycling and decrease potential crop yields by up to 17%in regions otherwise receiving this moisture in the form of precipitation (Bagley *et al.*, 2012).Changes in vegetation coverage and structure due to long-term climate change or shorter-term extreme events such as droughts (Anderegg *et al.*, 2013) also affect the partitioning of precipitation into evapotranspiration and runoff, sometimes involving complex feedbacks with the climate system such as in the Amazon region (Port *et al.*, 2012; Saatchi *et al.*, 2013). As water, carbon and vegetation dynamics evolve synchronously and interactively under climate change (Heyder *et al.*, 2011) in that e.g. vegetation structure and composition can dynamically adapt to changing climatic and hydrologic conditions (Gerten *et al.*, 2007), it remains a challenge to disentangle the effects of future land cover changes on the water cycle.

[INSERT FIGURE VW-1 HERE
Figure VW-1: Percentage change (ensemble median across 19 GCMs used to force a vegetation and hydrology model) in net irrigation requirements of 12 major crops by the 2080s, assuming current extent of irrigation areas and current management practices. Top: impacts of climate change only; bottom: additionally considering physiological and structural crop responses to increased atmospheric CO_2 concentration. Taken from Konzmann *et al.* (2013).]

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Box CC-WE. The Water-Energy-Food Nexus as Linked to Climate Change

[Douglas J. Arent (USA), Petra Döll (Germany), Ken Strzepek (UNU/USA), FerencToth (IAEA/Hungary), Blanca Elena Jimenez Cisneros (Mexico), Taikan Oki (Japan)]

Water, energy, and food are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure CC-WE-1. The depth and intensity of those linkages vary enormously between regions and production systems. Some energy technologies (biofuels, hydropower, thermal power plants), transportation fuels and modes and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops) require more water than others (Chapter 3.7.2, 7.3.2, 10.2,10.3.4, McMahon and Price, 2011, Macknick et al, 2012a, Cary and Weber 2008). In irrigated agriculture, climate, crop choice and yields determine water requirements per unit of produced crop, and in areas where water must be pumped or treated, energy must be provided (Kahn and Hajra 2009, Gertenet al. 2011). While food production and transport require large amounts of energy (Pelletier et al 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (7.3.2, Diffenbaugh et al 2012, Skaggs et al, 2012).

[INSERT FIGURE WE-1 HERE
Figure WE-1: The water-energy-food nexus as related to climate change.]

Most energy production methods require significant amounts of water, either directly (e.g. crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (Chapter 10.2.2 and 10.3.4, and Davies et al 2013, van Vliet et al 2012). Water is also required for mining, processing, and residue disposal of fossil fuels. Water for biofuels, for example, has been reported by Gerbens-Leenes et al. 2012 who computed a scenario of water use for biofuels for transport in 2030 based on the Alternative Policy Scenario of the IEA. Under this scenario, global consumptive irrigation water use for biofuel production is projected to increase from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water for energy currently ranges from a few percent to more than 50% of freshwater withdrawals, depending on the region and future water requirements will depend on electric demand growth, the portfolio of generation technologies and water management options employed (WEC 2010, Sattler et al., 2012). Future water availability for energy production will change due to climate change (Chapter 3.5.2.2).

Water may require significant amounts of energy for lifting, transport and distribution, treatment or desalination. Non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m^3 of water vary by about a factor of 10 between different sources, e.g. locally produced or reclaimed wastewater vs. desalinated seawater (Plappally and Lienhard 2012, Macknick et al, 2012b). Groundwater (35% of total global water withdrawals, with irrigated food production being the largest user, Döll et al. 2012) is generally more energy intensive than surface water – in some countries, 40% of total energy use is for pumping groundwater. Pumping from greater depth (following falling groundwater tables) increases energy demand significantly– electricity use (kWhr/m^3) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard 2012). A lack of water security can lead to increasing energy demand and vice versa, e.g. over-irrigation in response to electricity or water supply gaps.

Other linkages through land use and management, e.g. afforestation, can affect water as well as other ecosystem services, climate and water cycles (4.4.4, Box 25-10). Land degradation often reduces efficiency of water and energy use (e.g. resulting in higher fertilizer demand and surface runoff), and many of these interactions can compromise food security (3.7.2, 4.4.4). Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water (McCornick *et al.*, 2008, Bazilian *et al.*, 2011, Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy demand, bioproductivity and other factors (see Figure WE-1 and Wise et al, 2009), and has implications for security of supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction as well as the implications for health and economic impacts as described throughout this Assessment Report.

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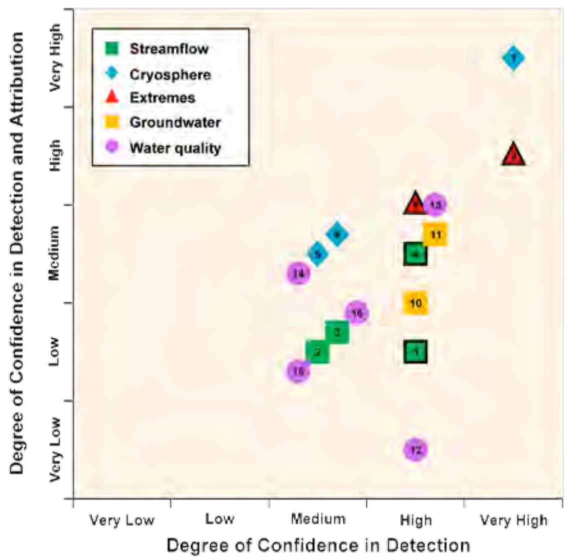
Table 3-1: Selected examples, mainly from Section 3.2, of the observation, detection and attribution of impacts of climate change on freshwater resources. Observed hydrological changes are attributed here to their climatic drivers, which are not all known to be anthropogenic; in the diagram, symbols with borders represent end-to-end attribution of the impact on resources to anthropogenic climate change.

1: Gedney et al. (2006a), Gerten et al. (2008); 2: Piao et al. (2010); 3: Shiklomanov et al. (2007); 4: Hidalgo et al. (2009); 5: Collins (2008); 6: Baraer et al. (2012); 7: Rosenzweig et al. (2007); 8: Min et al. (2011); 9: Pall et al. (2011); 10: Aguilera and Murillo (2009); 11: Jeelani (2008); 12: Evans et al. (2005); 13: Marcé et al. (2010); 14: Pednekar et al. (2005); 15: Paerl et al. (2006); 16: Tibby and Tiller (2007).



Observed change	*Attributed to*	*Ref*
Changed runoff (global and continental, 1960-1994)	Reduction of transpiration due to anthropogenic CO_2, but partly offset by more abundant vegetation	1
Reduced runoff (Yellow River, China)	Increased temperature; only 35% of reduction attributable to human withdrawals	2
Earlier annual peak discharge (Russian Arctic, 1960-2001)	Increased temperature and earlier spring thaw	3
Earlier annual peak discharge (Columbia River, western USA, 1950-1999)	Anthropogenic warming	4
Glacier meltwater yield greater in 1910-1940 than in 1980-2000 (European Alps)	Glacier shrinkage forced by comparable warming rates in the two periods	5
Decreased dry-season discharge (Peru, 1950s-2000)	Decreased glacier extent in the absence of a clear trend in precipitation	6
Disappearance of Chacaltaya Glacier, Bolivia (2009)	Ascent of freezing isotherm at 50 meters per decade	7
More intense extremes of precipitation (northern tropics and mid-latitudes, 1951-1999)	Anthropogenic greenhouse-gas emissions	8
Fraction of risk of flooding (England and Wales, autumn 2000)	Extreme precipitation attributable to anthropogenic greenhouse radiation	9
Decreased recharge of karst aquifers (Spain, 20th century)	Decreased precipitation, increased temperature leading to increased evapotranspiration	10
Decreased groundwater recharge (Kashmir, 1985-2005)	Decreased winter precipitation	11
Increased dissolved organic carbon in upland lakes (United Kingdom, 1988-2004)	Increased temperature and precipitation; multiple confounding factors	12
Increased anoxia in a reservoir, moderated during ENSO episodes (Spain, 1954-2007)	Decreased runoff due to decreased precipitation and increased evaporative demand	13
Variable faecal pollution in a saltwater wetland (California, 1969-2000)	Variable storm runoff; 70% of coliform variability attributable to variable precipitation	14
Nutrient flushing from swamps, reservoirs (North Carolina, 1970s-2002)	Hurricanes	15
Increased lake nutrient content (Victoria, Australia, 1984-2000)	Increased air and water temperature	16

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

Type of hydrological change or impact	Description of indicator	Hyd. change or impact in different emissions scenarios or different degress of global warming	Reference
Decreace of renewable water resources, global scale	Number of people affected by a water resources decrease of more than 20%, in percent of world population (multi-model mean)	Up to 2°C above present (2.7°C above pre-industrial), each degree of warming affects an additional 7%	Schewe *et al*. (submitted)
Decrease of renewable groundwater resources, global scale	Number of people affected by a groundwater resources decrease of more than 10%, in % of world population by the 2080s (mean and range of 5 GCMs)	RCP2.6: 24% (11-39%) RCP4.5: 26% (23-32%) RCP6.0: 32% (18-45%) RCP8.5: 38% (27-50%)	Portmann *et al*. (submitted)
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)
Change of groundwater recharge in the whole Australian continent	Probability that groundwater recharge decreases to less than 50% of 20th century value by 2050), based on ensemble of 16 GCMs	GW 1.0°C: close to 0 almost everywhere GW 2.4°C: in western Australia 0.2-0.6, in central Australia 0.2-0.3, elsewhere close to 1	Crosbie *et al*. (2012)
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 Roosmalen *et al*. (2007)
Population living in regions with high water stress	Percentage of global population living in regions of with a per-capita water availability of 1000 m^3/year (2080s, 1 GCM), population according to A2[1]	GW by 2050: 1°C: 62 2°C: 60 4°C: 55	Murray *et al*. (2012)
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)	GW 1°C, no change in atmosph. circulation: 3.1%, 124 days GW 2°C and change in	Bonte and Zwolsman (2010)

	2 Maximum duration of MAC exceedance (2050, 1 GCM)	atmosph. circulation: 14.3 %, 178 days Reference period: 2.5%, 103 days	
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)
Reduction in usable capacity of once-through or combination cooling thermal power plants in Europe and USA due to low river flow and excessive water temperature	Number of days per year with with a capacity reduction of more than 50% (for existing power plants) (2031-2060, 3 GCMs)	A2: 24 B1: 22 Without climate change: 16	van Vliet *et al*. (2012)
Flood damages in Europe (EU27)	1 Expected annual damages, in 2006- € 2 Expected annual population exposed (2080s, 2 GCMs)	A2: 18-21 billion €/year , 510.000-590.000 people B2: 14-15 billion €/year , 440.000-470.000 people Reference period: 6.4 billion €/year, 200.000 people	Feyen *et al*. (2012)
Flood damages in Japan	Expected annual damages, in Japanese Yen (¥)	Current 110 billion ¥/year, GCM20 (A1B): 200 billion ¥/year, MIROC-5 (RCP4.5) 150-500 billion ¥/year, MIROC-5 (RCP8.5) 150-330 billion ¥/year.	Fukubayashi *et al*. (2013)

GW: Global warming: mean global temperature increase relative to 1961-90
GCM: General circulation models

Table 3-3: Categories of climate change adaptation measures regarding to freshwater.
CC: Particular relevant to climate change, M+A: assist both mitigation and adaptation, M: also assist mitigation]

ADAPTATION OPTION	CC	M+A	M
Institutional			
Support integrated water resources management (IWRM) , including also the integrated management of land considering specifically negative and positive impacts of climate change		X	X
Promote synergy of water and energy savings and efficient use	X		X
Identify “no-regret policies” and build a portfolio of relevant solutions for adaptation	X		
Increase resilience by forming water utility network working teams	X		
Build adaptive capacity	X		
Improve and share information	X	X	X
Adapt the legal framework to make it instrumental to address climate change impacts	X	X	X
Develop financial tools (credit, subsidies and public investment) for the sustainable management of water, and considering poverty eradication and equity			

Design and operation			
Design and apply decision-making tools that consider uncertainty and fulfill multiple objectives	X		
Revise design criteria of water infrastructure to optimize flexibility, redundancy and robustness	X		
Ensure plans and services are robust, adaptable or modular, good value, maintainable, and with long-term benefits, especially in low income countries	X		
Operate water infrastructure increasing the resilience to climate change by all users and sectors			
Take advantage of using hard and soft adaptation measures			X
Perform programs to protect water resources in quantity and quality			
Increase resilience to climate change by diversifying water sources and improving the reservoir management			
Reduce water abstractions by reducing leaks, implementing water saving programs, cascading and reusing water	X	X (leaks)	
Improve design and operation of sewers and wastewater treatment infrastructure to cope with variations in influent quantity and quality	X		
Provide universal sanitation using technology and methodologies locally adapted and provided the proper disposal/reintegration of used water into the environment or its reuse			
Reduce impact of natural disasters			
Implement monitoring and early warning system			
Develop contingency plans			
Improve defense and site selection for key infrastructure that is at risk of floods	X		
Design cities suppressing and resilient to urban floods			
Actively seek and secure water from a diversity (spatially and source-type) of sources within the region to prevent impacts from droughts			
Promote the efficient use of water from all users and reduction of water demand			
Improve irrigation efficiency and reduce the demand of water for irrigation			X
Promote switching to more appropriate crops (drought resistant, saline resistant; low water demand)			
Apply flood or drought resistant crop varieties	X		
Agricultural irrigation			
Reuse wastewater to irrigate crops and use soil for carbon sequestration	X(partly)		X
Industrial use			
When selecting alternative sources of energy, assess the need for water			
Relocate water-thirsty industries and crops to water rich areas			
Implement industrial water efficiency certifications			

With information from: Arkell *et al*. (2011a; 2011b); Andrews (2009); Bahri (2009); Bowes *et al*., (2012); de Graaf and van der Brugge (2010); Dembo (2010); Dillon and Jiménez (2008); Elliot *et al*. (2011); Emelko *et al*. (2011); Godfrey *et al*. (2010) ; Jiménez (2011); Jiménez and Asano (2008b) ; Keller (2008) ; Kingsford (2011); Mackay (2010); Major *et al*. (2011); Marsalek *et al*. (2006); McCafferty (2008); McGuckin (2008); Mukhopadhyay and Dutta (2010); Munashinghe (2010); Mogaka *et al*. (2006); NACWA (2009); OECD (2010); OFWAT (2009); Reiter (2009); Renofalt *et al*. (2010); Seah (2008); Sprenger *et al*. (2011); Thöle (2008); UNESCO (2011); UNHABITAT (2008); Vörösmarty *et al*. (2000); Whitehead *et al*. (2009b); Zwolsman *et al*. (2010)

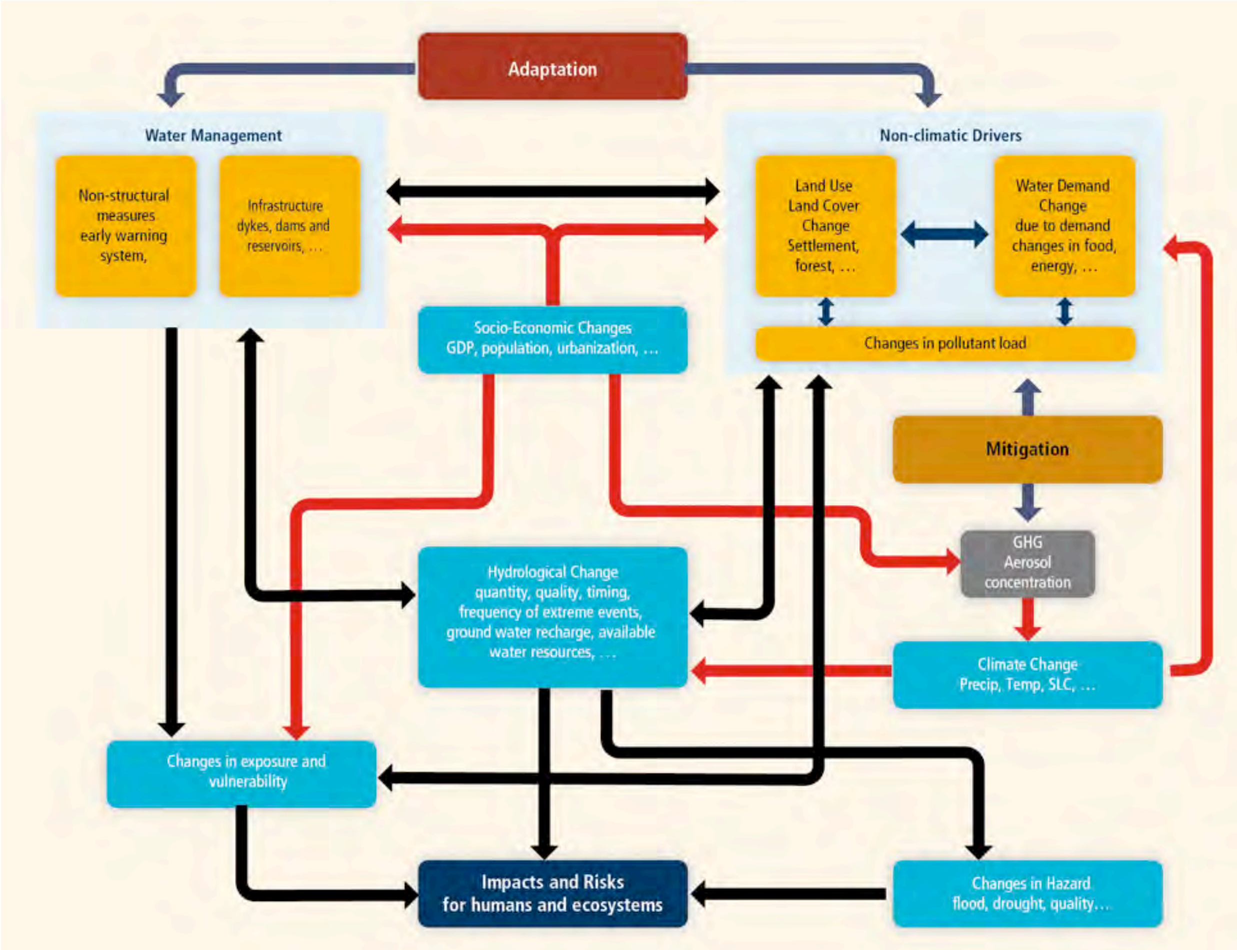


Figure 3-1: Framework for considering the impacts of climate change on freshwater systems and society. Socio-economic changes, such as GDP, population, and urbanization, will change the way of water managements, exposure and vulnerability of human beings against water related risks, and non-climatic drivers changing water management in terms of quantity and quality, as well as emissions and concentration of Green House Gases (GHGs) and Aerosol, that will lead to changes in precipitation, temperature, and sea level. Water management, non-climatic drivers, and climate change will alter hydrological cycles, and lead to change the impacts and risks for humans and ecosystems in conjunction with the changes in exposure and vulnerability, and hazards such as flood and drought. Water management consists with measures developing infrastructure, such as dykes, dams, and reservoirs, and non-structural measures, such as early warning system. Land cover and land use changes including afforestation, deforestation, and settlement, change of water demand due to economic development and demand changes in food and energy, and anthropogenic changes in pollutant load are examples of non-climatic drivers, and they are inter-acting each other. Mitigation acts on the emission and concentration of GHGs as well as on non-climatic drivers, while adaptation acts on non-climatic drivers and water management which alters exposure and vulnerability. (modified from Figure 3-1, AR4)

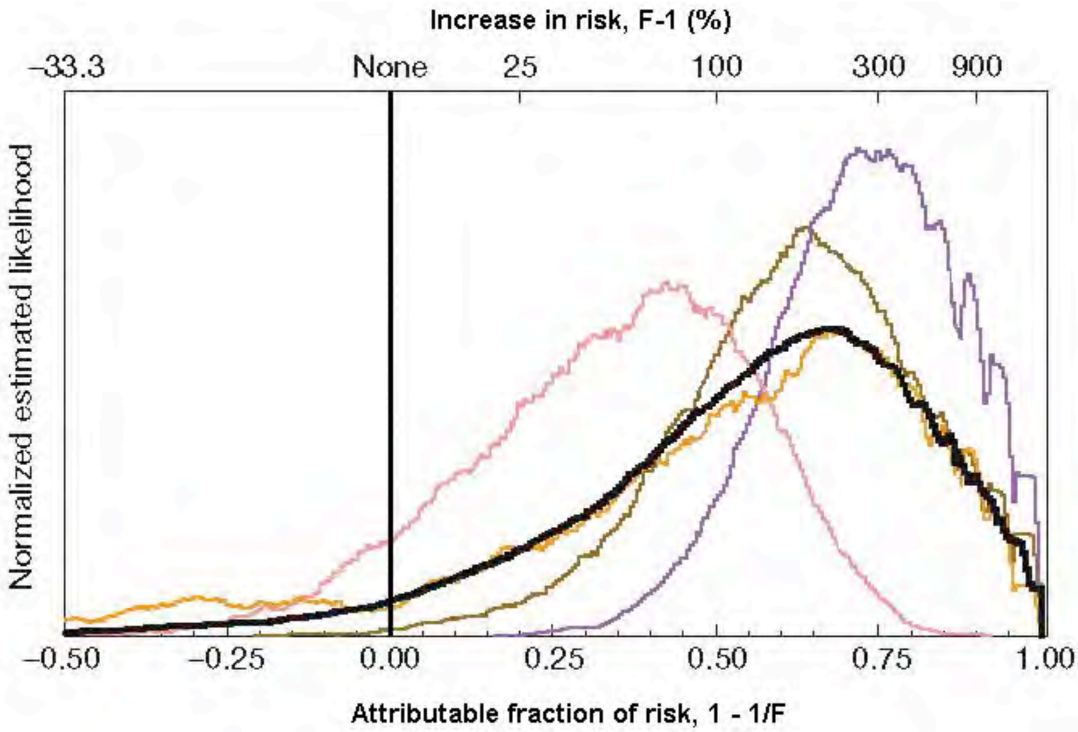
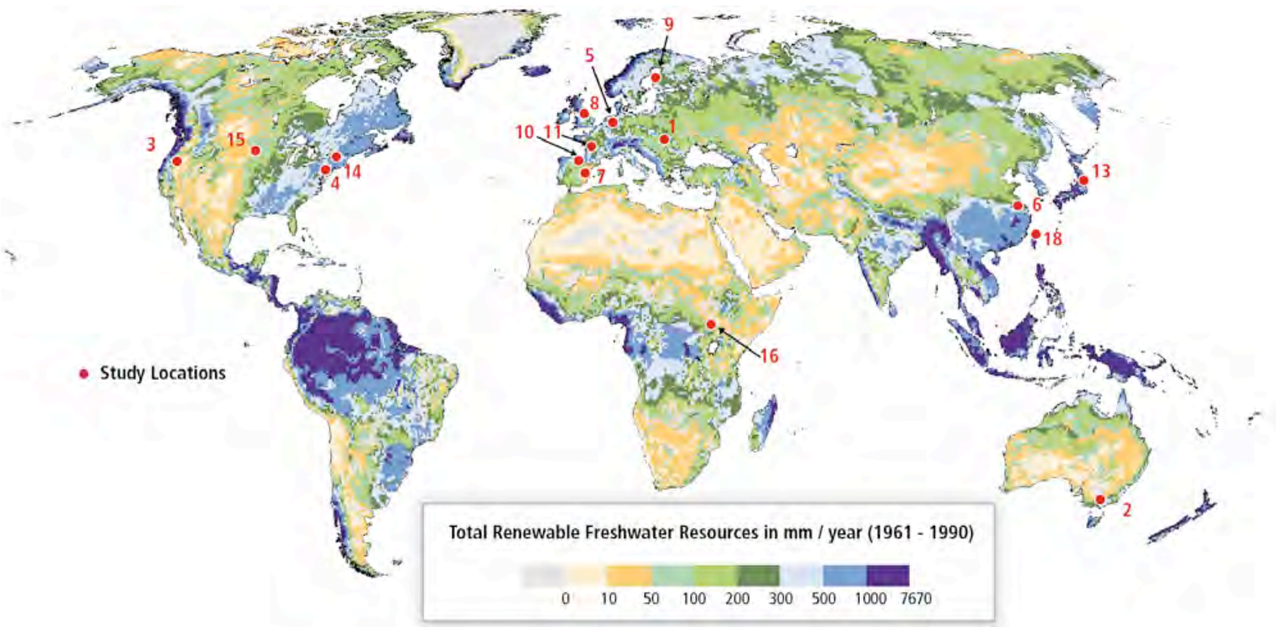


Figure 3-2: Likelihood distributions of the ratio *F* of risks of flooding in England and Wales in autumn 2000 in several thousand paired simulations without and with anthropogenic greenhouse forcing (based on Pall *et al*., 2011; see also Bindoff *et al*., 2013 (WGI Chapter 10)). Each pair starts from a unique initial state that differs slightly from a common reference state. Vertical line represents no change in risk due to anthropogenic greenhouse forcing. Thin coloured lines: distributions with anthropogenic forcing, obtained with a seasonal-forecast model driven by patterns of attributable warming found beforehand from four climate-model simulations of the 20th century; the forecast model is coupled to a model of basin-scale runoff and hydraulics. Thick black line: aggregate of the four distributions.



#	Location	Study Period	Observation	Reference
1	Dabube River, Bratsilava, Slovakia	1926-2005	Although the Water temperature is rising the trend of the weighted long term average temperature valus is near zero. Nevertheless the interannual distribution of the average monthly discharged was modified	Halmova et al., 2008
2	Purrumbete, Colac & Bullen Merri Lakes, Victoria, Australia	1984-2000	The increase in air temperature associated with the increase in salinity and nutrient content in water. Increase in salinity as results of variations in effective precipitation	Tibby and Tiller, 2007
3	Lake Tahoe, California and Nevada Sates, US	1970-2007	Increased temperature induced increased thermal stability lowered the dissolved oxygen content	Sahoo et al., 2010
4	Neuse River Estuary, North Carolina, US	1970-1990s	Large storms and hurricanes assited to flush nutrients from the estuatry reducing eutrophication conditions	Paerl et al., 2006; 2008
5	Rriver Meuse, western Europe	1976-2003	Deterioration of the quality of water in terms or temperature, major elements and some heavy metals and metalloids due to droughts. Higher water temperaturescombined with a reduction of the dilution capacity of point source effluents and longer residence time lead to higher nutrient concentrations that induced algae blooms	Van Vliet and Zwolsman, 2008
6	Lake Taihu, Wuxi, Jiangsu, China	2007	The lake that was suffering increased frequencies, intensities and more larger of cyanobacterial blooms. In May, 2007, it suffered an unusual massive bloom that lead to the presence of Microcystis toxins in water. This forced two million people from Taihu city to dring bottled water for a week. This was attributed to an unusually warm spring	Qin et al., 2010
7	Sau Reservoir, Spain	1964-2007	Stream flow variations were of greater significance than temperature increases in the depletion of dissolved oxygen from water	Marce et al., 2010
8	22 upland waters in UK	1988-2002	Dissolved organic increase due to a range of potential drivers, including temperature, rainfall, acid deposition, land-use, nitrogen and CO2 enrichment	Evans et al., 2005
9	Coastal rivers from western Finland	1913-2007	pH (low values) were associated with maximum discharges in rivers because higher rainfalls in bassins with AS (acid sulphate) soils	Sarinen et al., 2010
		1961-2007	CODMs critical values were associated with maximum discharges in rivers because higher rainfalls in bassins with AS (acid sulphate) soils	
10	15 montan pristine rivers from northern Spain	1973-2005	Clear relationship among air temperature increase and the deterioration of water quality (nutrient and COD content in semi arid streams;	Benítez-Gilabert et al., 2010
11	30 coastal rivers and groundwater of Western France	2-6 years	Inter-annual variations on the nutrient content in surface water were realted to changes on air temperature, rainfall and management practices. These variations were not observed on groundwater because of the delay on the response time and the effect of the soil on water.	Gascuel-Odoux et al., 2011
12	Ginock, Scottia	Near 11 years	Higher risks of fecal pollution clearly related to rainfall during the wet period	Tetzlaff et al., 2010
13	Japanese streams		Increases on the air temperature were related to increased on the chemical oxygen demand on water, being these higher than those observed from precipitation in arid and semiarid zones	Ozaki et al., 2003
14	SW Penssylvania waters			Chang 2004
15	US	1948-1994	Rainfall and runoff were implicated in site-specific waterborne disease outbreaks	Curriero et al., 2001
16	Northern and Eastern Uganda	1999-2001, 2004, 2007	Elevated concentrations of faecal pathogens in groundwater-fed water supplies during the rainy season	Tunwine et al. 2002, 2003; Taylor et al., 2008
17	Walkerton			Auld et al., 2004
18	Taiwan		Epidemic and contamination with enterovirus of a well for supply due to an increased rainfall rate	Jean et al., 2006

Figure3-3: Observations and projections of the impacts on the quality of water. (under production)

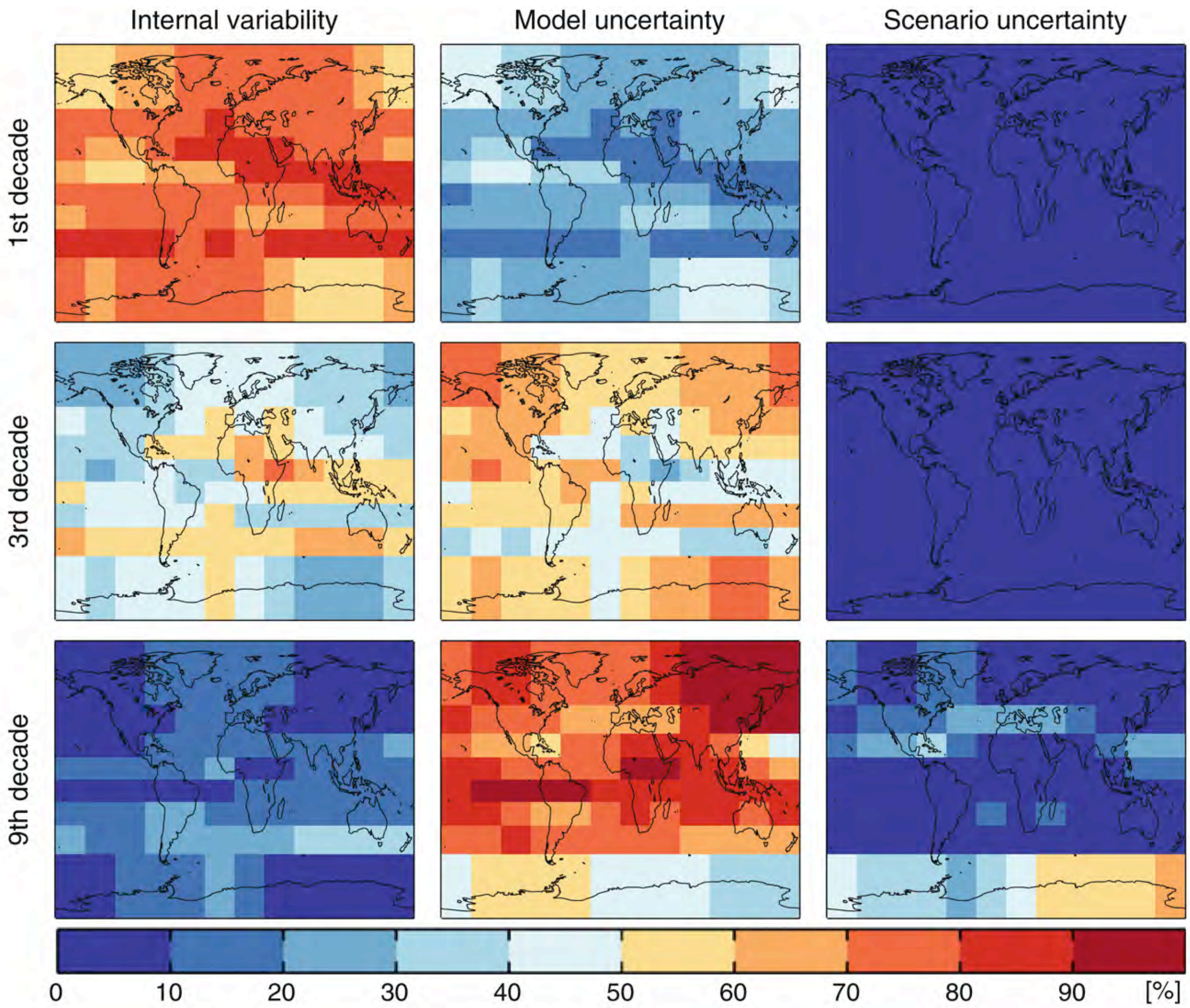


Figure 3-4: Variance in projections of changes in decadal-mean precipitation for boreal summer (June, July, and August), decomposed into contributions from three sources of uncertainty. Simulations were for 2000-2100 under the SRES A1B, A2 and B1 scenarios, with one ensemble member taken from each of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

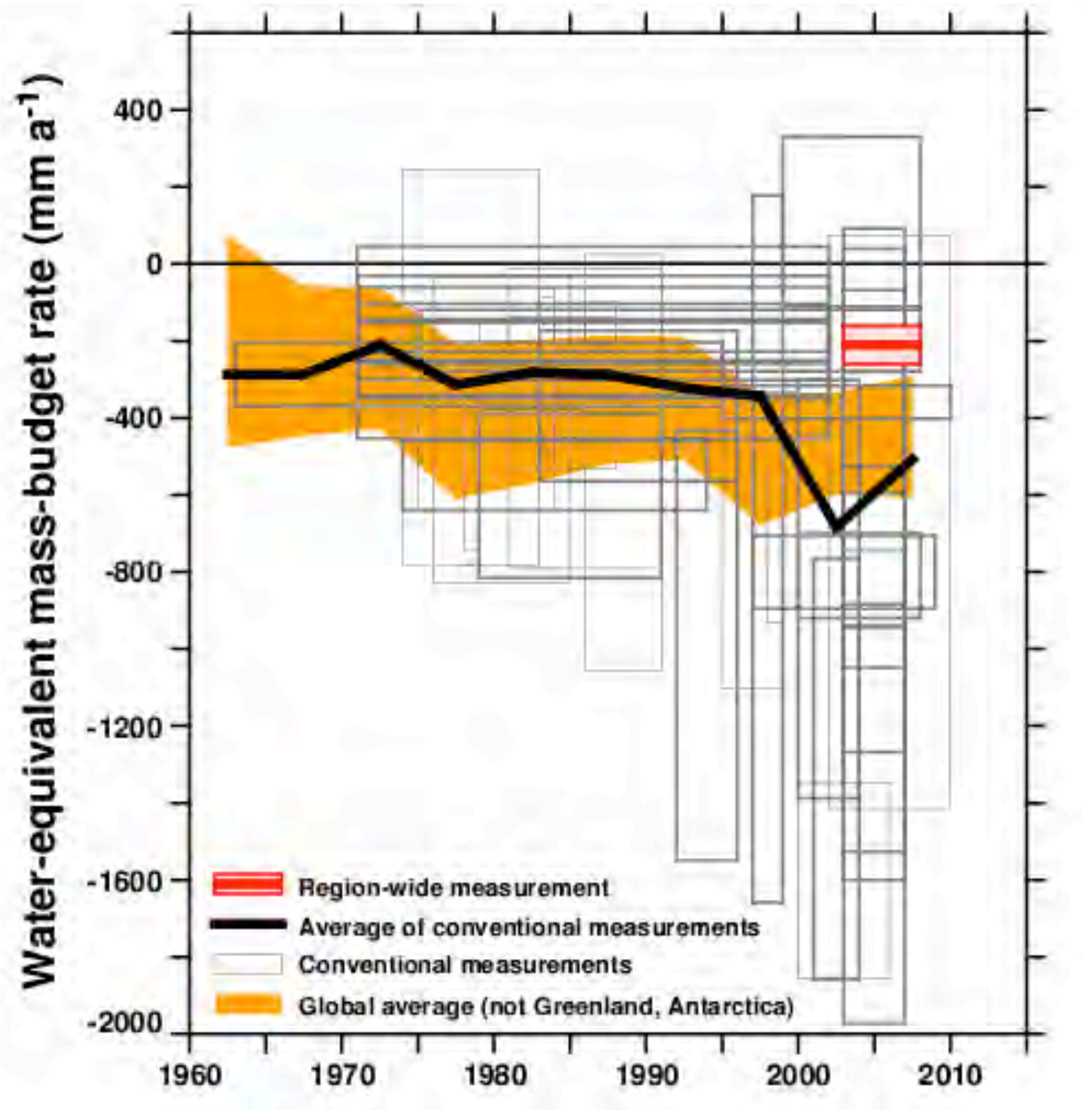


Figure 3-5: A compilation of all published glacier mass balance measurements from the Himalaya (based on Bolch *et al.*, 2012). Each measurement is shown as a box of height ±1 standard deviation centred on the average balance (±1 standard error for multi-annual measurements). Region-wide measurement (Kääb *et al.*, 2012) was by satellite laser altimetry. Global average (Comiso *et al.*, 2013 (WGI Chapter 4)) is shown as a 1-sigma confidence region.

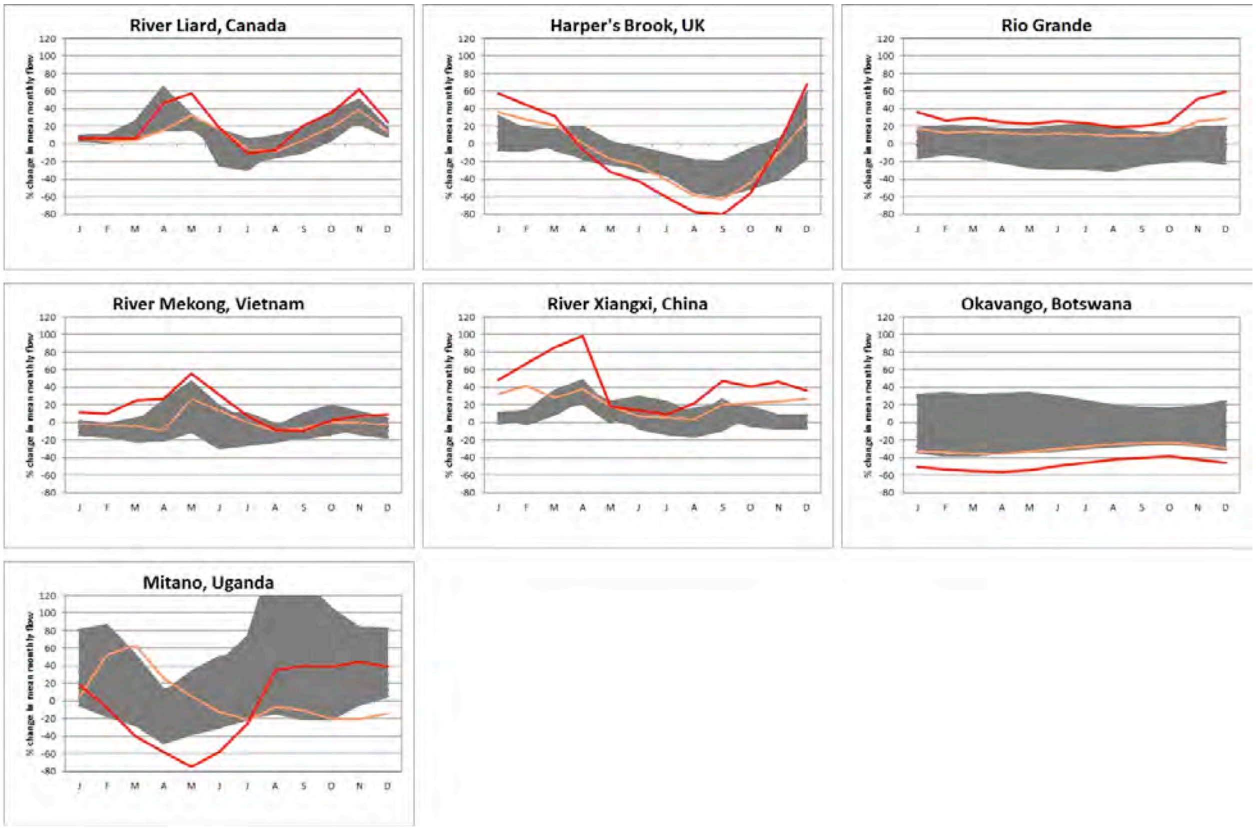


Figure 3-6: Range in change in mean monthly runoff across seven climate models in seven catchments, with a 2ºC increase in global mean temperature (above 1961-1990) (Arnell, 2011b; Hughes *et al*., 2011; Kingston and Taylor, 2010; Kingston *et al*., 2011; Nobrega *et al*., 2011; Thorne, 2011a; Xu *et al*., 2011). Changes with the HadCM3 climate model with increases of 2 and 4ºC are highlighed.

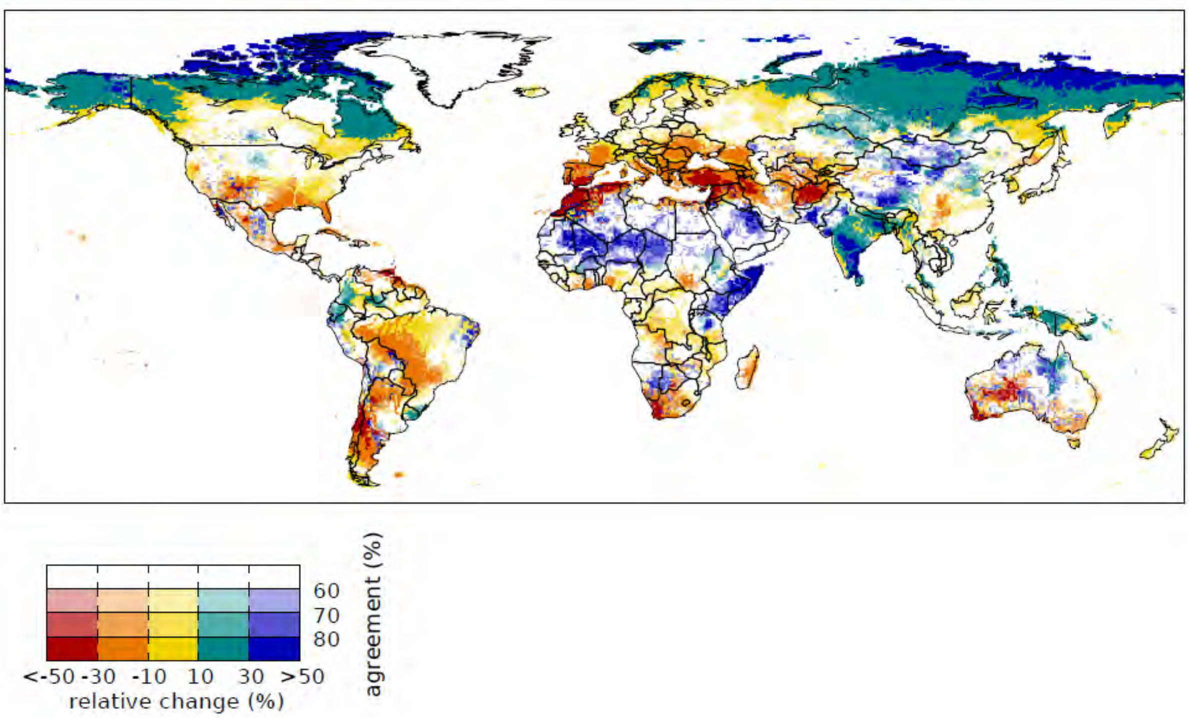


Figure 3-7: Relative change in annual discharge at 2°C (2.7°C above pre-industrial) compared to present-day, under RCP8.5. Color hues show the multi-model mean change, and saturation shows the agreement on the sign of change across all 55 GHM-GCM combinations (percentage of model runs agreeing on the sign). (Schewe *et al*., 2013)

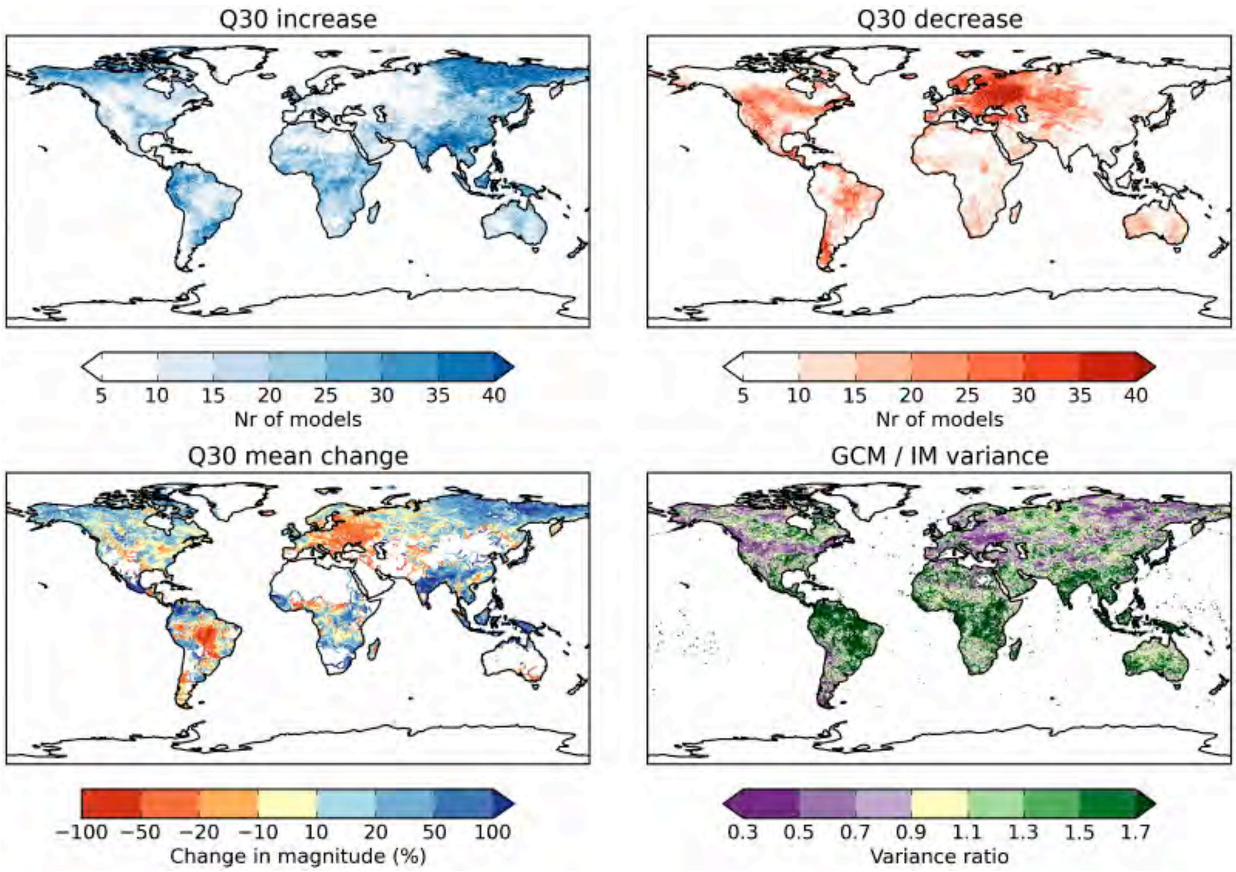


Figure 3-8: Results of flood hazard change for the 30-year return level of river flow (Q30) from ensemble of 5 CMIP5 GCM simulations under RCP8.5 coupled with nine global hydrology and land surface models (named as impact models (IMs)) that provided simulations of daily river discharge at a global 0.5-degree grid for two 30-year periods (1971-2000 and 2070-2090) (Dankers *et al*., 2013). Top: Number of experiments (out of 45 in total) showing an increase (top left) or decrease (top right) in the magnitude of Q30 of more than 10% in 2070-2099 under RCP8.5, compared to 1971-2000. Bottom left: Average change in the magnitude of Q30 across all experiments. Bottom right: Ratio of GCM variance to IM variance. GCM variance was computed as the variance of the change in Q30 across all GCMs for each individual IM, and then averaged over the 9 IMs; IM variance was computed as the variance of the change in Q30 across all IMs for each individual GCM, and then averaged over the 9 GCMs. In dark green (purple) areas GCM (IM) variance predominates.

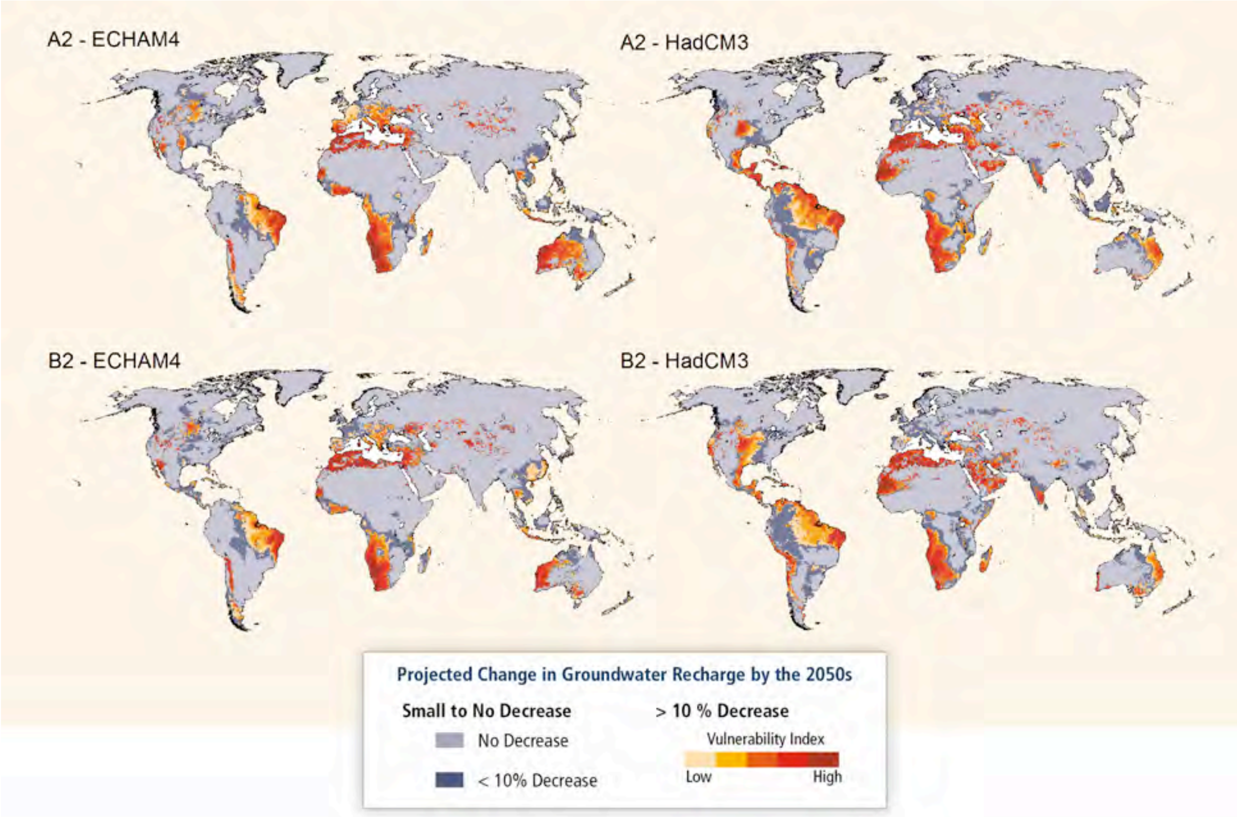


Figure 3-9: Human vulnerability to climate change induced decreases of renewable groundwater resources by the 2050s for four climate change scenarios in which lower (B2) and higher (A2) emissions pathways are interpreted by two global climate models. The higher the vulnerability index (computed by multiplying 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).

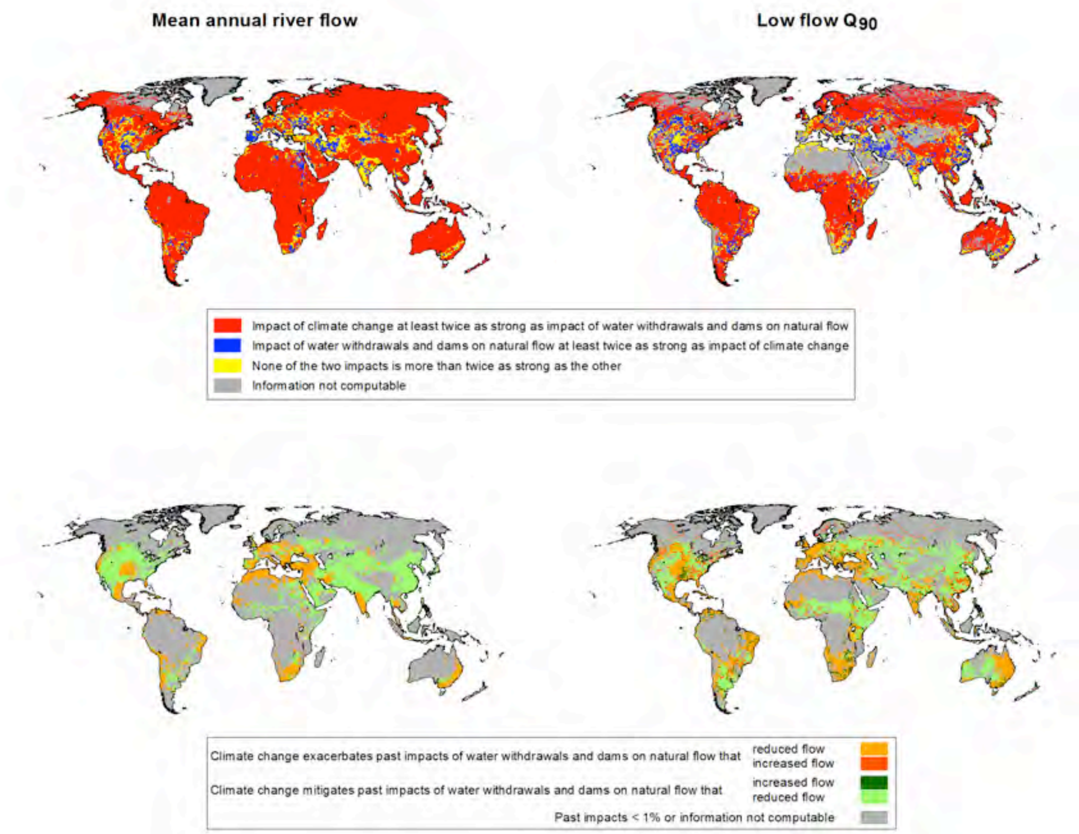


Figure RF-1: Impact of climate change on the ecologically relevant river flow characteristics mean annual river flow and monthly low flow Q_{90} as compared to the impact of water withdrawals and dams on natural flows, as computed by a global water model (Döll and Zhang, 2010). Impact of climate change is the percent change of flow between 1961-1990 and 2041-2070 according to the emissions scenario A2 as implemented by the global climate model HadCM3. Impact of water withdrawals and reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002.

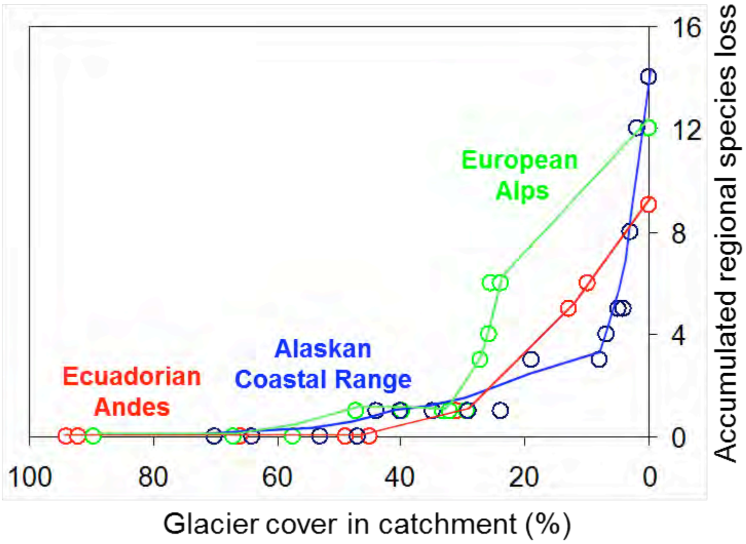


Figure RF-2: Accumulated loss of regional species richness (gamma diversity) as a function of glacial cover GCC. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%. Each data point represents a river site and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.

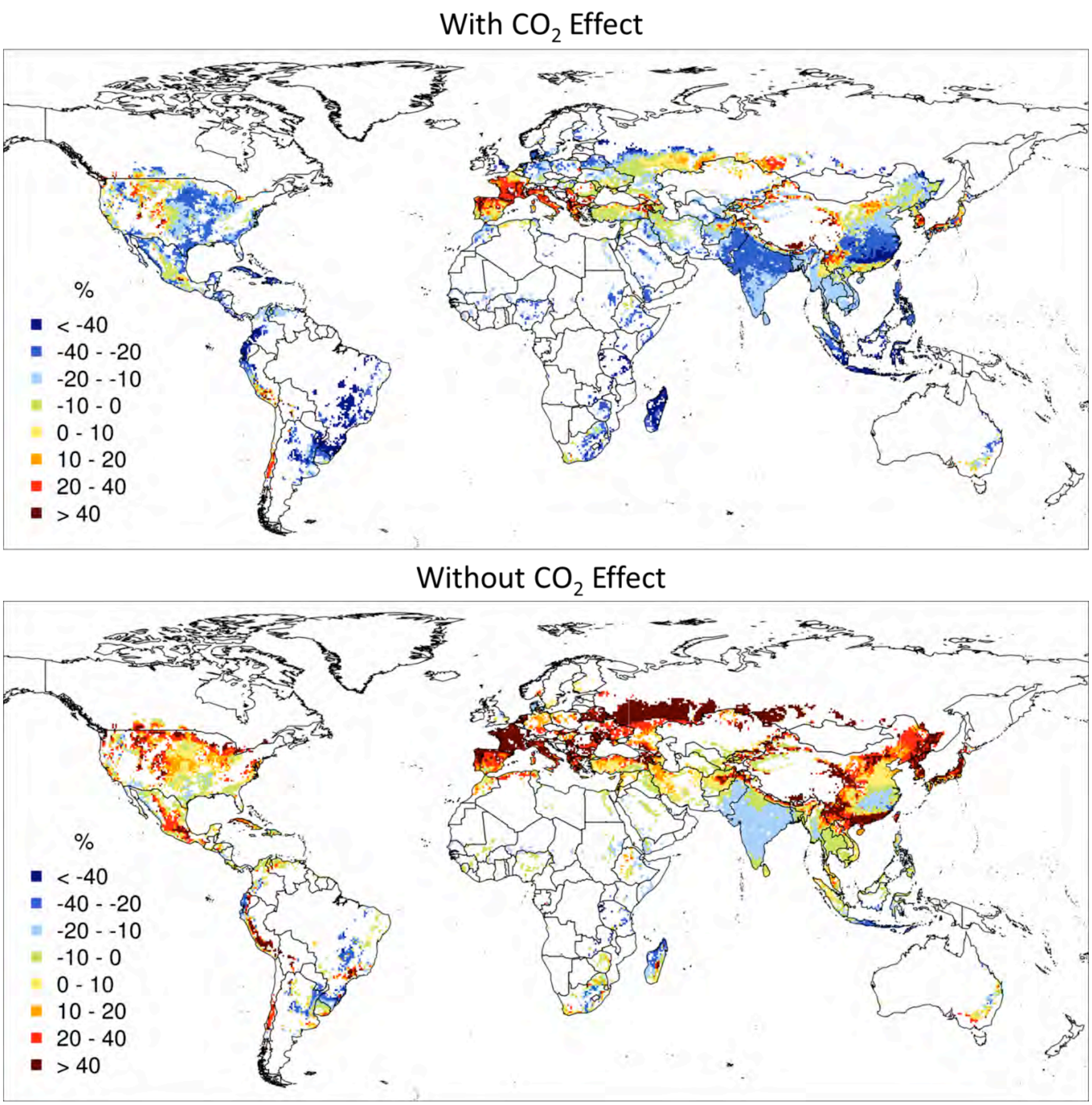


Figure VW-1: Percentage change (ensemble median across 19 GCMs used to force a vegetation and hydrology model) in net irrigation requirements of 12 major crops by the 2080s, assuming current extent of irrigation areas and current management practices. Top: impacts of climate change only; bottom: additionally considering physiological and structural crop responses to increased atmospheric CO_2 concentration. Taken from Konzmann *et al.* (2013).

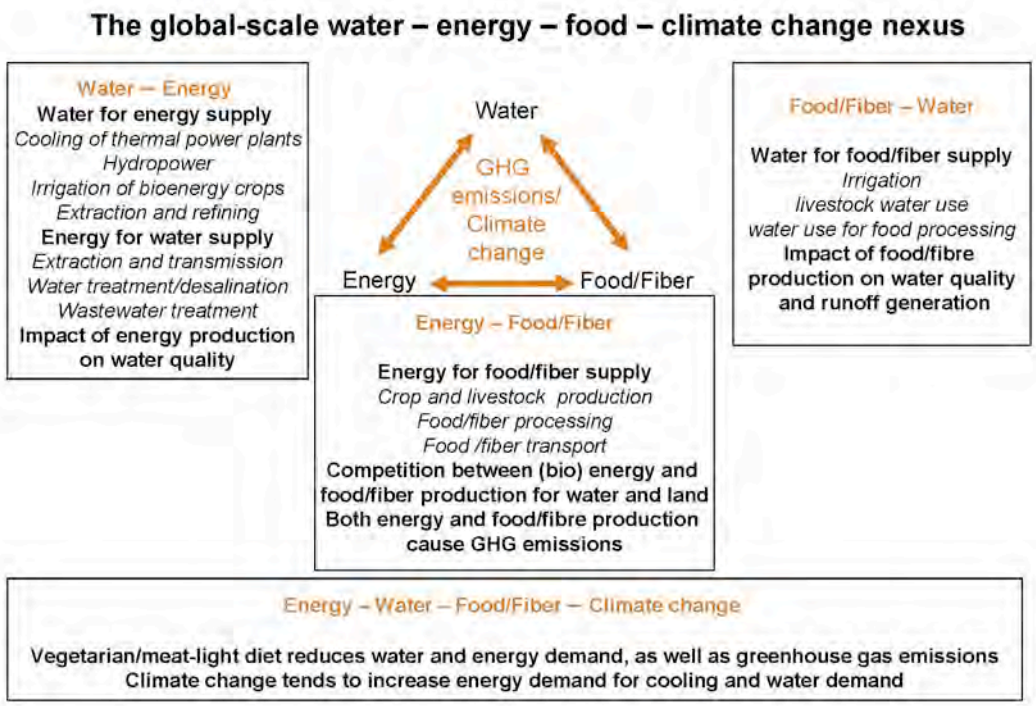


Figure WE-1: The water-energy-food nexus as related to climate change.