Chapter 3. Freshwater Resources

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Executive Summary

Key risks at the global scale

Freshwater-related risks of climate change increase significantly with increasing greenhouse gas emissions (*high agreement, robust evidence*) [3.4; 3.5]. Modelling studies since AR4, with large but better quantified uncertainties, have demonstrated clear differences between global futures with higher emissions, which have stronger adverse impacts, and those with lower emissions, which cause less damage and cost less to adapt to [Table 3-2]. Each degree of warming is projected to decrease renewable water resources by at least 20% for an additional 7% of the global population. By the end of the 21st century, the number of people exposed annually to a 20th-century 100-year flood is projected to be three times greater for very high emissions (RCP8.5) than for very low emissions (RCP2.6) [Table 3-2; 3.4.8].

Climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions (*high agreement, robust evidence*) [3.4; 3.5]. This will exacerbate competition for water among agriculture, ecosystems, settlements, industry and energy production, affecting regional water, energy and food security [3.5.1; 3.5.2; Box CC-WE]. In contrast, water resources are projected to increase at high latitudes. Proportional changes are typically one to three times greater for runoff than for precipitation. The effects on water resources and irrigation requirements of changes in vegetation due to increasing greenhouse-gas concentrations and climate change remain uncertain [Box CC-VW].

So far there are no widespread observations of changes in flood magnitude and frequency due to anthropogenic climate change, but projections imply variations in the frequency of floods (*medium agreement,*

***limited evidence*).** Flood hazards are projected to increase in parts of south, southeast and northeast Asia, tropical Africa, and South America (*medium agreement, limited evidence*). Since the mid-20th century, socio-economic losses from flooding have increased mainly due to greater exposure and vulnerability (*high confidence*). Global flood risk will increase in the future partly due to climate change (*medium agreement, limited evidence*) [3.2.7; 3.4.8].

Climate change is *likely* to increase the frequency of meteorological droughts (less rainfall) and agricultural droughts (less soil moisture) in presently dry regions by the end of this century under the RCP8.5 scenario (*medium confidence*) [WGI Ch12]. This is *likely* to increase the frequency of short hydrological droughts (less surface water and groundwater) in these regions (*medium agreement, medium evidence*) [3.4.8]. Projected changes in the frequency of droughts longer than 12 months are more uncertain, because these depend on accumulated precipitation over long periods. There is no evidence that surface water and groundwater drought frequency has changed over the last few decades, although impacts of drought have increased mostly due to increased water demand [3.5.1].

Climate change negatively impacts freshwater ecosystems by changing streamflow and water quality (*high agreement, medium evidence*). Quantitative responses are known in only a few cases. Except in areas with intensive irrigation, the streamflow-mediated ecological impacts of climate change are expected to be stronger than historical impacts due to anthropogenic alteration of flow regimes by water withdrawals and the construction of reservoirs [Box CC-RF; 3.5.2.4].

Climate change is projected to reduce raw water quality, posing risks to drinking water quality even with conventional treatment (*high agreement, medium evidence*). The sources of the risks are increased temperature, increases in sediment, nutrient and pollutant loadings due to heavy rainfall, reduced dilution of pollutants during droughts, and disruption of treatment facilities during floods [3.2.5; Figure 3-2; 3.4.6; 3.5.2.3].

In regions with snowfall, climate change has altered observed streamflow seasonality, and increasing alterations due to climate change are projected (*high agreement, robust evidence*) [Table 3-1; 3.2.3; 3.2.7; 3.4.5; 3.4.6; 26.2.2]. Except in very cold regions, warming in the last decades has reduced the spring maximum snow depth and brought forward the spring maximum of snowmelt discharge; smaller snowmelt floods, increased winter flows and reduced summer low flows have all been observed. River ice in Arctic rivers has been observed to break up earlier [3.2.3; 28.2.1.1].

Because nearly all glaciers are too large for equilibrium with the present climate, there is a committed water-resources change during much of the 21st century, and changes beyond the committed change are expected due to continued warming; in glacier-fed rivers, total meltwater yields from stored glacier ice will increase in many regions during the next decades but decrease thereafter (*high agreement, robust evidence*). Continued loss of glacier ice implies a shift of peak discharge from summer to spring, except in monsoonal catchments, and possibly a reduction of summer flows in the downstream parts of glacierized catchments [3.4.3].

There is little or no observational evidence yet that soil erosion and sediment loads have been altered significantly due to changing climate (*medium agreement, limited evidence*). However, increases in heavy rainfall and temperature are projected to change soil erosion and sediment yield, although the extent of these changes is highly uncertain and depends on rainfall seasonality, land cover, and soil management practices [3.2.6; 3.4.7].

Adaptation, mitigation, and sustainable development

Of the global cost of water-sector adaptation, most is necessary in developing countries where there are many opportunities for anticipatory adaptation (*high agreement, medium evidence*). There is limited published information on the water-sector costs of adaptation at the local level [3.6.1; 3.6.3].

An adaptive approach to water management can address uncertainty due to climate change (*high agreement, limited evidence*). Adaptive techniques include scenario planning, experimental approaches that involve learning from experience, and the development of flexible and low-regret solutions that are resilient to uncertainty. Barriers to progress include lack of human and institutional capacity, financial resources, awareness, and communication [3.6.1; 3.6.2; 3.6.4].

Reliability of water supply, which is expected to suffer from increased variability of surface water availability, may be enhanced by increased groundwater abstractions (*high agreement, limited evidence*). This adaptation to climate change is limited in regions where renewable groundwater resources decrease due to climate change [3.4.5; 3.4.8; 3.5.1].

Some measures to reduce greenhouse gas emissions imply risks for freshwater systems (*high agreement, medium evidence*). If irrigated, bioenergy crops make water demands that other mitigation measures do not. Hydropower has negative impacts 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 and soil erosion [3.7.2.1; Box CC-WE].

3.1. Introduction

Changes in the hydrological cycle due to climate change can lead to diverse impacts and risks, and they are conditioned by and interact with non-climatic drivers of change and water-management responses (Figure 3-1). Water is the agent that delivers many of the impacts of climate change to society, for example to the energy, agriculture, and transport sectors. Even though water moves through the hydrological cycle, it is a locally variable resource, and vulnerabilities to water-related hazards such as floods and droughts differ between regions. Anthropogenic climate change is one of many stressors of water resources. Non-climatic drivers such as population increase, economic development, urbanization, and land-use or natural geomorphic changes also challenge the sustainability of resources by decreasing water supply or increasing demand. In this context, adaptation to climate change in the water sector can contribute to improving the availability of water.

[INSERT FIGURE 3-1 HERE
Figure 3-1: Framework (boxes) and linkages (arrows) for considering impacts of climatic and social changes on freshwater systems, and consequent impacts on and risks for humans and freshwater ecosystems. Both climatic (Section 3.3.1) and non-climatic (Section 3.3.2) drivers have changed natural freshwater systems (Section 3.2) and are expected to continue to do so (Section 3.4). They also stimulate adaptive measures (Section 3.6). Hydrological and water-management changes interact with each other and with measures to mitigate climate change (Section 3.7.2). Adaptive measures influence the exposure and vulnerability of human beings and ecosystems to water-related risks (Section 3.5).]

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 observed and projected impacts of climate change on freshwater systems and their management are mainly due to 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.
- Warmer water, more intense precipitation, and longer periods of low flow reduce water quality, with impacts on ecosystems, human health, and reliability and operating costs of water services.
- Climate change affects water-management infrastructure and practice.
- Adaptation 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 hydrological changes due to climate change, mainly based on research published since AR4. 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 Chapter 10 for detection and attribution, Chapter 11 for near-term projections, and Chapter 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). 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. Sections 3.2.7, 3.4.8 and 3.6.3 discuss impact costs and adaptation costs related to water resources; these costs are assessed more broadly in Chapter 10.

3.2. Observed Hydrological Changes due to Climate Change

3.2.1. Detection and Attribution

A documented hydrological change is not necessarily due to anthropogenic climate change. Detection entails showing, usually statistically, that part of the documented change is not due to natural variability of the water cycle (Chapter 18; WGI Chapter 10). For robust attribution to climatic change, all the drivers of the hydrological change must be identified, with confidence levels assigned to their contributions. Human contributions such as water withdrawals, land-use change and pollution mean that this is usually difficult. Nevertheless, many hydrological impacts can be attributed confidently to their climatic drivers (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 most catchment-scale 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 result from climatic changes that may in turn result partly from 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, not all of which are necessarily anthropogenic; in the diagram, symbols with borders represent end-to-end attribution of the impact on resources to anthropogenic climate change.
1: Gerten *et al*. (2008), Piao *et al.* (2010), Alkama *et al.* (2011); 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 magnitude. Call this fraction r_{ctrl} in the simulated actual climate and r_{expt} in the simulated climate in which there is no anthropogenic forcing, and suppose there are many paired instances of r_{ctrl} and r_{expt}, with the ratio of risks in each pair given by $F = r_{\mathrm{expt}}/r_{\mathrm{ctrl}}$. The distribution of risk ratios F describes the likelihood that the climate change has altered the risk. Several thousand pairs of such simulations were run to estimate the risk ratio for the floods in England and Wales in autumn 2000 (Pall *et al.*, 2011). Each pair started from a unique initial state that differed slightly from a common reference state, and was 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 was coupled to a model of basin-scale runoff and channel-scale hydraulics. It is not probable that such exercises will become routine for assessing single-event risks in, for example, the insurance industry, because the necessary amount of computation was so formidable. Nevertheless, the result was compelling: in each of the four sets of simulation pairs, the risk increased greatly on average in the runs forced by anthropogenic greenhouse radiation. In aggregate, the most probable amount of increase was two- to three-fold, and at most a few percent of the simulation pairs suggested that anthropogenic forcing actually decreased the risk. This summary is worded carefully: the thousands of simulation pairs were needed for quantifying the uncertainties, which led unavoidably to a spread of likelihoods, and thus to statements about uncertainty about risk that are themselves uncertain.

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; WGI Chapter 2). According to regional observations, most droughts and extreme rainfall events of the 1990s and 2000s have been the worst since the 1950s (Arndt *et al*., 2010) and certain trends in total and extreme precipitation amounts are observed (WGI Chapter 2). Most regional changes in precipitation are attributed either to internal variability of the atmospheric circulation or to global warming (Lambert *et al*., 2004; Stott *et al*., 2010). It was estimated that the 20th-century anthropogenic forcing contributed significantly to observed changes in global and regional precipitation (Zhang *et al*., 2007). Changes in snowfall amounts are indeterminate, as for precipitation; however, consistent with observed warming, shorter snowfall seasons are observed over most of the Northern Hemisphere, with snowmelt seasons starting earlier (Takala *et al*., 2009). In Norway, increased temperature at lower altitudes has reduced the snow water equivalent (Skaugen *et al*., 2012).

Steady decreases since the 1960s of global and regional actual evapotranspiration and pan evaporation have been attributed to changes in precipitation, in diurnal temperature range, aerosol concentration, (net) solar radiation, vapour pressure deficit, and wind speed (Fu *et al*., 2009; McVicar *et al*., 2010; Miralles *et al*., 2011; Wang A. *et al*., 2011). Regional downward and upward trends in soil moisture content have been calculated for China from 1950 to 2006, where longer, more severe and more frequent soil moisture droughts have been experienced over 37% of the land area (Wang A. *et al*., 2011). This is supported by detected increases since the 1960s in dry days and a prolongation of dry periods (Fischer *et al.*, 2013; Gemmer *et al*., 2011), and can be attributed to increases in warm days and warm periods (Fischer *et al.*, 2011).

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 (WGI Chapter 4) and the Andes (Rabassa, 2009). Active layer depth and permafrost degradation are closely dependent on soil ice content. In steep terrain, slope stability is highly affected by changes in permafrost (Harris *et al*., 2009). The release of GHGs (greenhouse gases) 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). In most parts of the world glaciers are losing mass (Gardner *et al.*, 2013). For example, almost all glaciers in the tropical Andes have been shrinking rapidly since the 1980s (Rabassa, 2009; Rabatel *et al.*, 2013); similarly, Himalayan glaciers are losing mass at present (Bolch *et al.*, 2012).

3.2.3. Streamflow

Detected trends in streamflow are generally consistent with observed regional changes in precipitation and temperature since the 1950s. In Europe, streamflow (1962-2004) 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 (1951-2002), increases were observed in the Mississippi basin and decreases in the US Pacific Northwest and southern Atlantic-Gulf regions (Kalra *et al*., 2008). In China, a decrease in streamflow in the Yellow River (1960-2000) is consistent with a reduction of 12% in summer and autumn precipitation, whereas the Yangtze shows a small increase in annual streamflow driven by an increase in monsoon rains (Piao *et al*., 2010; see Table 3-1). 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 urbanization (Wang and Cai, 2010).

In a global analysis of simulated streamflows (1948-2004), 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). The contribution to observed streamflow changes due to decreased stomatal opening of many plant species at higher CO_2 concentration remains disputed (Box CC-VW).

In regions with seasonal snow storage, warming since the 1970s has led to earlier spring discharge maxima (*high agreement, robust evidence*) and has increased winter 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 streamflow is lower in summer, decrease in snow storage has 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 these additional influences. The extent to which groundwater abstractions have already been affected by climate change is not known. Both detection of changes in groundwater systems and attribution of those changes to climatic changes are rare, 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) since the 1980s 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 not only decreased strongly during the 20th century due to the decreasing precipitation but that groundwater recharge as a fraction of observed precipitation declined progressively, possibly indicating an increase in evapotranspiration (Aguilera and Murillo, 2009; Table 3-1).

3.2.5. Water Quality

Most observed changes of water quality due to climate change (Table 3-1; Figure 3-2) are known from isolated studies, mostly of rivers or lakes in high-income countries, of a small number of variables. In addition, even though some studies extend over as many as 80 years, most are short-term. For lakes and reservoirs, the most frequently reported change is more intense eutrophication and algal blooms at higher temperatures, or shorter hydraulic retention times and higher nutrient loads resulting from increased storm runoff (*high agreement, medium to robust evidence*). Greater runoff results in greater loads of salts, faecal coliforms, pathogens and heavy metals (Boxall *et al*., 2009; Paerl *et al.*, 2006; Pednekar *et al.*, 2005; Tibby and Tiller, 2007) (*medium to high agreement, robust evidence*, depending on the pollutant). In some cases there are associated impacts on health. For instance, hospital admissions for gastrointestinal illness in elderly people increased by 10% when turbidity increased in the raw water of a drinking water plant even when treated using conventional procedures (Schwartz *et al*., 2000). However, positive impacts were also reported. For example, the risk of eutrophication was reduced when nutrients were flushed from lakes and estuaries by more frequent storms and hurricanes (Paerl and Huisman, 2008). For rivers, all reported impacts on water quality were negative. Greater runoff, instead of diluting pollution, swept more pollutants from the soil into watercourses (*medium to high agreement, robust evidence*) (Benítez-Gilabert *et al*., 2010; Boxall *et al*., 2009; 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). Increased organic matter content impaired the quality of conventionally treated drinking water (Weatherhead and Howden, 2009). In streams in semiarid and arid areas, temperature changes had a stronger influence on the increase of organic matter, nitrates and phosphorus than precipitation changes (Benítez-Gilabert *et al.*, 2010; Chang, 2004; Ozaki *et al.*, 2003) (*medium agreement, limited evidence*). Studies of impacts on groundwater quality are limited and mostly report elevated concentrations of faecal coliforms during the rainy season or after extreme rain events (*high agreement, medium evidence*), with varying response times (Auld *et al*., 2004; Curriero *et al*., 2001; Jean *et al*., 2006; Seidu *et al*., 2013; Tumwine *et al*., 2002; 2003). Given the widespread use of groundwater for municipal supply and minimal or lacking treatment of drinking water in poor regions, increased pollution is a source of concern (Jean *et al.*, 2006; Seidu *et al*., 2013). Another concern is the nonlinearity (except for temperature) of relationships between water quality and climatic variables (*medium agreement, limited evidence*). In general, the linkages between observed effects on water quality and climate should be interpreted cautiously and at the local level, considering the type of water body, the pollutant of concern, the hydrological regime and the many other possible sources of pollution (*high confidence*, 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).

[INSERT FIGURE 3-2 HERE
Figure 3-2: Observations of the impacts of climate on water quality.]

3.2.6. Soil Erosion and Sediment Load

Precipitation extremes in many regions have increased since 1950 (Seneviratne *et al*., 2012), which suggests an increase in rainfall erosivity that would enhance soil erosion and stream sediment loads. A warmer climate may affect soil moisture, litter cover and biomass production, and can bring about a shift in winter precipitation from snow to more erosive rainfall (Kundzewicz *et al*., 2007) or, in semiarid regions, an increase in wildfires with subsequent rainfall leading to intense erosive events (Bussi *et al*., 2013; Nyman *et al*., 2011). The effects of climate change on soil erosion and sediment load are frequently obscured by human agricultural and management activities (Walling, 2009).

Only few studies have isolated the contribution of climate change to observed trends in soil erosion and sediment load. In the Yellow River basin, where soil erosion results mostly from heavy rainfall, reduced precipitation (~10%) contributed about 30% to a total reduction in stream sediment loads reaching the sea during 2000-2005, compared to 1950-1968, with the remaining 70% attributable to sediment trapping in reservoirs and soil conservation measures (Miao *et al*., 2011; Wang *et al*., 2007). Dai *et al*. (2008), analyzing the decrease in sediment load of the Yangtze River over 1956-2002, found that climate change was responsible for an increase of about 3±2%; most of the decline in its lower reaches was due to dam construction (Three Gorges Dam) and soil conservation measures.

Potential impacts of climate change on soil erosion and sediment production are of concern in regions with pronounced glacier retreat (Walling, 2009). Glacial rivers are expected to discharge more meltwater, which may increase sediment loads. However, the *limited evidence* is inconclusive for a global diagnosis of sediment load changes; there are both decreasing (e.g. Iceland, Lawler *et al*., 2003) and increasing trends (Patagonia, Fernandez *et al*., 2011). So far, there is no clear evidence that the frequency or magnitude of shallow landslides have 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 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 agreement* and *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 impacts of land-use and land-cover changes are more significant than those of climate change.

3.2.7. Extreme Hydrological Events 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 (Kundzewicz *et al*., 2013). The strength of the evidence is limited mainly by lack of long-term records from unmanaged catchments. Moreover, in the attribution of detected changes it is difficult to distinguish the roles of climate and human activities (Section 3.2.1). However, recent detection of trends in extreme precipitation and discharge in some catchments implies greater risks of flooding at regional scale (*medium confidence*). More locations show increases in heavy precipitation than decreases (Seneviratne *et al*., 2012). Flood-damage costs worldwide have been increasing since the 1970s, although this is partly due to increasing exposure of people and assets (Handmer *et al*., 2012).

There is no strong evidence for trends in observed flooding in the USA (Hirsch and Ryberg, 2012), Europe (Benito and Machado, 2012; Hannaford and Hall, 2012; Mudelsee *et al*., 2003; Stahl *et al*., 2010), South America, and Africa (Conway *et al*., 2009). However, at smaller spatial scales, an increase in annual maximum discharge has been detected in parts of northwestern Europe (Giuntoli *et al*., 2012; Hattermann *et al*., 2012; Petrow and Merz, 2009), while a decrease was observed in southern France (Giuntoli *et al*., 2012). Flood discharges in the lower Yangtze basin increased over 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% 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 Arctic rivers dominated by a snowmelt regime, there is no general trend in flood magnitude and frequency (Shiklomanov *et al*., 2007). In Nordic countries, significant changes since the mid-20th century are mostly towards earlier seasonal flood peaks, but flood magnitudes show contrasting trends, driven by temperature and precipitation, in basins with and without glaciers: increasing peaks in the former and decreasing peaks in the latter (Dahlke *et al*., 2012; Wilson *et al*., 2010). Significant trends at almost one fifth of 160 stations in Canada were reported, most of them decreases in snowmelt-flood magnitudes (Cunderlik and Ouarda, 2009). 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 explainable in terms of increasing frequency and persistence of circulation patterns favourable to flooding (Petrow *et al*., 2009). It is *very likely* that the observed intensification of heavy precipitation is largely anthropogenic (Min *et al.*, 2011; see also Section 3.2.1).

Socio-economic losses from flooding are increasing (*high confidence*), although attribution to anthropogenic climate change is established only seldom (Pall *et al.*, 2011). Reported flood damages (adjusted for inflation) have increased from an average of 7 billion US$ per year in the 1980s to about 24 billion US$ per year in 2011 (Munich Re, 2012; Kundzewicz *et al*., 2013). 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 are higher in developing countries. Since 1980, the annual number of flood-related deaths has been in the thousands, with over 95% in developing countries and 75% in southern, southeastern and eastern Asia (Handmer *et al*., 2012). There is *high confidence* (*high agreement*, *medium evidence*) that greater exposure of people and assets, and societal factors related to population and economic growth, contributed to the increased losses (Handmer *et al*., 2012; Kundzewicz *et al*., 2013). When damage records are normalized for changes in exposure and vulnerability (Bouwer, 2011), most studies find no contribution of flooding trends to the trend in losses (Barredo, 2009; Benito and Machado, 2012; Hilker *et al*., 2009), although there are exceptions (Chang *et al*., 2009; Jiang *et al*., 2005).

Assessments of observed changes in ‘drought’ depend on the definition of drought (meteorological, agricultural or hydrological) and the chosen drought index (e.g. consecutive dry days, Standardised Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), Standardised Runoff Index (SRI); see Seneviratne *et al.*, 2012). Meteorological (rainfall) and agricultural (soil moisture) droughts have become more frequent since 1950 (Seneviratne *et al*., 2012) in some regions, including southern Europe and western Africa, but in others (including the southern USA; Chen *et al*., 2012) there is no evidence of change in frequency (WGI Chapter 2).

Very few studies have considered variations over time in hydrological (streamflow) drought, largely because there are few long records from catchments without direct human interventions. A trend was found towards lower summer minimum flows for 1962–2004 in small catchments in southern and eastern Europe were found, but there was no clear trend in northern or western Europe (Stahl *et al*., 2010). Models can reproduce observed patterns of drought occurrence (e.g. Prudhomme *et al*., 2011), but as with climate models their outputs can be very divergent. In simulations of drought at the global scale in 1963–2000 with an ensemble of hydrological models, strong correlations were noted between ENSO (El Niño-Southern Oscillation) events and hydrological droughts, and – particularly in dry regions – low correlations between meteorological and hydrological droughts, which suggests that hydrological droughts cannot necessarily be inferred from rainfall deficits (van Huijgevoort *et al*., 2013).

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 atmospheric water-vapor content, 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 have changed little (WGI Chapter 2). Among other climatic drivers are atmospheric carbon dioxide, which affects plant transpiration (Box CC-VW), and deposited black carbon and dust, both of which, even in very small concentrations, enhance melting of snow and ice by reducing the surface albedo.

Uncertainty in the climatic drivers is due mainly to internal variability of the atmospheric system, inaccurate modelling of the atmospheric response to external forcing, and the external forcing itself as described by the Representative Concentration Pathways (RCPs; Section 1.1.3 in Chapter 1). Internal variability and variation between models account for all of the uncertainty in precipitation in the first few decades of the 21st century in CMIP (Coupled Model Intercomparison Project) Phase 3 projections (Hawkins and Sutton, 2011). The contribution of internal variability diminishes progressively. By no later than mid-century, most of the uncertainty in precipitation is due to discrepancies between models, and divergent scenarios never contribute more than one third of the uncertainty. In contrast, the uncertainty in temperature (WGI Chapter 11) is due mostly to divergent scenarios.

CMIP5 simulations of the water cycle during the 21st century (WGI Chapter 12), with further constraints added here from 20th-century observations, can be summarized as follows:

- Surface temperature, which affects the vapor-carrying capacity of the atmosphere and the ratio of snowfall to precipitation, increases non-uniformly, but by about 1.5 times more over land than over ocean (*very high confidence*).
- Warming is greatest over the Arctic (*very high confidence*), implying latitudinally variable changes in snowmelt and glacier mass budgets.
- Less precipitation falls as snow and snow cover decreases in extent and duration (*high confidence*). In the coldest regions, however, increased winter snowfall outweighs increased summer snowmelt.
- Wet regions and seasons become wetter and dry regions and seasons become drier (*high 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).
- Global mean precipitation increases in a warmer world (*virtually certain*), but with substantial variations, including some decreases, from region to region. Precipitation tends to decrease in subtropical latitudes, particularly in the Mediterranean, Mexico and central America and parts of Australia, and to increase elsewhere, notably at high northern latitudes and in India and parts of central Asia (*likely* to *very likely*; WGI Chapter 12, Figure 12-41). However, precipitation changes generally become statistically significant only when temperature rises by at least 1.4°C, and in many regions projected 21st-century changes lie within the range of late-20th-century natural variability (Mahlstein *et al.*, 2012).
- Changes in evaporation have patterns similar to those of changes in precipitation, with moderate increases almost everywhere, especially at higher northern latitudes (Figure 12-25 in WGI Chapter 12). Scenario-dependent decreases of soil moisture are widespread, particularly in central and southern Europe, southwestern North America, Amazonia and southern Africa (*medium to high confidence*; Figure 12-23 and Section 12.4.5.3 in WGI Chapter 12).

More intense extreme precipitation events are expected (IPCC, 2012). One proposed reason is the projected increase in specific humidity: intense convective precipitation in short periods (less than 1 hour) tends to “empty” the water vapor from the atmospheric column (Berg *et al.*, 2013; Utsumi *et al.*, 2011). Annual maxima of daily precipitation that are observed to have 20-year return periods in 1986-2005 are projected to have shorter return periods in 2081-2100: about 14 years for RCP2.6, 11 years for RCP4.5 and 6 years for RCP8.5 (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 4-10% K^{-1}. Agreement between model-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 models is the dominant contributor to uncertainty. Model-simulated changes in the incidence of meteorological (rainfall) 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 impacts of climate change, the future of freshwater systems will be impacted strongly by demographic, socio-economic and technological changes, including lifestyle changes. These change both exposure to hazard and requirements for water resources. A wide range of socio-economic futures can produce similar climate changes (van Vuuren *et al*., 2012), meaning that certain projected hydrological changes (Section 3.4) can occur under a wide range of future demographic, social, economic and ecological conditions. Similarly the same future socio-economic conditions can be associated with a range of different climate futures.

Changing land use is expected to affect freshwater systems strongly in the future. For example, increasing urbanization may increase flood hazards and decrease groundwater recharge. Of particular importance for freshwater systems is future agricultural land use, especially irrigation, which accounts for about 90% of global water consumption and severely impacts freshwater availability for humans and ecosystems (Döll, 2009). Due mainly to population and economic growth but also 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 caused by climate change (Taylor R. *et al*., 2013a).

3.4. Projected Hydrological Changes

3.4.1. Methodological Developments in Hydrological Impact Assessment

Most recent studies of the potential impact of climate change on hydrological characteristics have used a small number of climate scenarios. An increasing number has used larger ensembles of regional or global models (e.g. Arnell, 2011; Arnell and Gosling, 2013; Bae *et al*., 2011; Chiew *et al*., 2009; Gosling *et al*., 2010; Jackson *et al*., 2011; Kling *et al*., 2012; Olsson *et al*., 2011). Some studies have developed "probability distributions" of future impacts by combining results from multiple climate projections and, sometimes, different emissions scenarios, making different assumptions about the relative weight to give to each scenario (Brekke *et al*., 2009b; Christierson *et al*., 2012; Liu *et al*., 2013; 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. Very few impact studies (Dankers *et al*., 2013; Hanasaki *et al*., 2013; Portmann *et al*., 2013; Schewe *et al*., 2013) have so far used scenarios based on CMIP5 climate models, and these have only used a small subset.

Most assessments have used a hydrological model with the "delta method" to create scenarios, which applies projected changes in climate derived from a climate model either to an observed baseline or with a stochastic weather generator. Several approaches to the construction of scenarios at the catchment scale have been developed (Fowler *et al*., 2007), including dynamical downscaling using regional climate models and a variety of statistical approaches (e.g. Fu *et al*., 2013). Systematic evaluations of different methods have demonstrated that estimated impacts can be very dependent on the approach used to downscale climate model data, and the range in projected change between downscaling approaches can be as large as the range between different climate models (Chen J. *et al*., 2011; Quintana Segui *et al*., 2010). An increasing number of studies (e.g. Fowler and Kilsby, 2007; Hagemann *et al*., 2011; Kling *et al*., 2012; Teutschbein and Seibert, 2012; Veijalainen *et al*., 2012; Weiland *et al*., 2012a) have run hydrological models with bias-corrected input from regional or global climate model output (Piani *et al*., 2010; van Pelt *et al*., 2009; Yang *et al*., 2010), rather than by applying changes to an observed baseline. The range between different bias correction methods can be as large as the range between climate models (Hagemann *et al*., 2011), although this is not always the case (Chen C. *et al*., 2011; Muerth *et al*., 2013). Some studies (e.g. Falloon and Betts, 2006; 2010; Hirabayashi *et al*., 2008; Nakaegawa *et al*., 2013) have examined changes in global-scale river runoff as simulated directly by a high-resolution climate model, rather than by an “off-line” hydrological model. Assessments of the ability of climate models directly to simulate current river flow regimes (Falloon *et al*., 2011; Weiland *et al*., 2012b) show that performance largely depends on simulated precipitation and is better for large basins, but the limited evidence suggests that direct estimates of change are smaller than off-line estimates (Hagemann *et al*., 2013).

The effects of hydrological model parameter uncertainty on simulated runoff changes are typically small when compared with the range from a large number of climate scenarios (Arnell, 2011; Cloke *et al*., 2010; Lawrence and Haddeland, 2011; Steele-Dunne *et al*., 2008; Vaze *et al*., 2010). However, the effects of hydrological model structural uncertainty on projected changes can be substantial (Dankers *et al*., 2013; Hagemann *et al*., 2013; Schewe *et al*., 2013), due to differences in the representation of evaporation and snowmelt processes. In some regions (e.g. high latitudes; Hagemann et al., 2013) with reductions in precipitation (Schewe *et al*., 2013)), hydrological model uncertainty can be greater than climate model uncertainty – although this is based on small numbers of climate models. Much of the difference in projected changes in evaporation is due to the use of different empirical formulations (Milly and Dunne, 2011). In a study in southeast Australia, the effects of hydrological model uncertainty were small compared with climate model uncertainty, but all the hydrological models used the same potential evaporation data (Teng *et al.*, 2012).

Among other approaches to impact assessment, an inverse technique (Cunderlik and Simonovic, 2007) starts by identifying the hydrological changes which would be critical for a system and then uses a hydrological model to determine the meteorological conditions which trigger those changes; the future likelihood of these conditions is estimated by inspecting climate model output, as in a catchment study in Turkey (Fujihara *et al*., 2008a; 2008b). Another 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, 2012; Renner *et al*., 2012). A response surface showing change in flood magnitudes was constructed by running a hydrological model with systematically-varying changes in climate (Prudhomme *et al*., 2010). This approach show the sensitivity of a system to change, and also allows rapid assessment of impacts under specific climate scenarios which can be plotted on the response surface.

3.4.2. Evapotranspiration, Soil Moisture and Permafrost

Based on global and regional climate models as well as physical principles, potential evapotranspiration over most land areas is *very likely* to increase in a warmer climate, thereby accelerating the hydrologic cycle (WGI Chapter 12). Long-term projections of actual evapotranspiration are uncertain in both magnitude and sign. They are affected not only by rising temperatures but also by changing net radiation and soil moisture, decreases in bulk canopy conductance associated with rising CO_2 concentrations, and vegetation changes related to climate change (Box CC-VW; Katul and Novick, 2009). Projections of the response of potential evapotranspiration to a warming climate are also uncertain. Based on six different methodologies, an increase in potential evapotranspiration was associated with global warming (Kingston *et al*., 2009). Regionally, increases are projected in southern Europe, Central America, southern Africa and Siberia (Seneviratne *et al.*, 2010). The accompanying decrease in 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, soil-moisture droughts lasting 4–6 months 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 (Sheffield and Wood, 2008). Because of strong natural variability, the generally monotonic projected increases are statistically indistinguishable from current climate.

Changes consistent with warming are also evident in the freshwater systems and permafrost of northern regions. The area of permafrost is projected to continue to decline over the first half of the 21st century in all emissions scenarios (Figure 4-18 in WGI Chapter 4). Under RCP2.6, permafrost area is projected to stabilize at near 20% less than the 20th century area, and then begin to increase slightly.

3.4.3. Glaciers

All projections for the 21st century (WGI Chapter 13) show continued mass loss from glaciers. In glacierized catchments, runoff reaches an annual maximum in summer. 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* in most regions, although not, for example, in the eastern Himalaya where the monsoon and the melt season coincide. The relative importance of high-summer glacier meltwater can be substantial, for example contributing 25% of August discharge in basins draining the European Alps, with area ~10^5 km^2 and only 1% glacier cover (Huss, 2011). Glacier meltwater also increases in importance during droughts and heat waves (Koboltschnig *et al*., 2007).

If the warming rate is constant, and if, as expected, ice melting per unit area increases and total ice-covered area decreases, the total annual yield passes through a broad maximum: "peak meltwater". Peak-meltwater dates have been projected between 2010 and 2050 (parts of China, Xie *et al.*, 2006); 2010–2040 (European Alps, Huss, 2011); and mid- to late-century (glaciers in Norway and Iceland, Jóhannesson *et al.*, 2012). Note that the peak can only be dated relative to a specified reference date. Declining yields relative to various dates in the past have been detected in some observational studies (Table 3-1); that is, a peak has been passed already. There is *medium confidence* that the peak response to 20th- and 21st-century warming will fall within the 21st century in many inhabited glacierized basins, where at present society is benefitting from a transitory "meltwater dividend". Variable forcing leads to complex variations of both the melting rate and the extent of ice, which depend on each other.

If they are in 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

The total freshwater resource in the Himalayan glaciers of Bhutan, China, India, Nepal and Pakistan is known only roughly; estimates range from 2100 to 5800 Gt (Bolch *et al*., 2012). Their 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. A recent large-scale measurement, highlighted in Figure 3-3, is the first well-resolved, region-wide measurement of any component of the Himalayan water balance. It suggests strongly that the conventional measurements, mostly on small, accessible glaciers, are not regionally representative.

[INSERT FIGURE 3-3 HERE
Figure 3-3: All published glacier mass balance measurements from the Himalaya (based on Bolch *et al*., 2012). To emphasize the variability of the raw information, 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 (WGI Chapter 4) is shown as a 1-sigma confidence region.]

Glacier mass changes for 2006-2100 were projected by simulating the response of a glacier model to CMIP5 projections from 14 general circulation models (GCMs) (Radić *et al*., 2013). Results for the Himalaya range between 2% gain and 29% loss to 2035; to 2100, the range of losses is 15-78% under RCP4.5. The model-mean loss to 2100 is 45% under RCP4.5 and 68% under RCP8.5 (*medium confidence*). It is *virtually certain* that these projections are more reliable than an earlier erroneous assessment (Cruz *et al*., 2007) of complete disappearance by 2035.

At the catchment scale, projections do not yet present a detailed region-wide picture. However the GCM-forced simulations of Immerzeel *et al.* (2013) in Kashmir and eastern Nepal show runoff increasing throughout the century. Peak ice meltwater is reached in mid- to late-century, but increased precipitation over-compensates for the loss of ice.

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

The hazard due to moraine-dammed ice-marginal lakes continues to increase. 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). There has been little progress on the predictability of dam failure but, of five dams that have failed since 1980, all had frontal slopes steeper than 10° before failure and much gentler slopes afterwards (Fujita *et al*., 2013). This is a promising tool for evaluating the hazard in detail.

The relative importance of Himalayan glacier meltwater decreases downstream, being greatest where the runoff enters dry regions in the west and becoming negligible in the monsoon-dominated east (Kaser *et al*., 2010). In the mountains, however, dependence on and vulnerability to glacier meltwater are of serious concern when measured per head of population.

_____ END BOX 3-1 HERE _____

3.4.4. Runoff and Streamflow

Many of the spatial gaps identified in AR4 have been filled to a very large extent by catchment-scale studies of the potential impacts of climate change on streamflow. 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: the smaller the ratio, the greater the sensitivity. Proportional changes in average annual runoff are typically between one and three times as large as proportional changes in average annual precipitation (Tang and Lettenmaier, 2012).

Projected scenario-dependent changes in runoff at the global scale, mostly from CMIP3 simulations, exhibit a number of consistent patterns (e.g. Arnell and Gosling, 2013; Döll and Zhang, 2010; Fung *et al*., 2011; Hirabayashi *et al*., 2008; Murray *et al*., 2012; Nakaegawa *et al*., 2013; Okazaki *et al*., 2012; Schewe *et al*., 2013; Tang and Lettenmaier, 2012; Weiland *et al*., 2012a). Average annual runoff is projected to increase at high latitudes and in the wet tropics, and to decrease in most dry tropical regions. However, for some regions there is very considerable uncertainty in the magnitude and direction of change, specifically in China, south Asia and large parts of South America. Both the patterns of change and the uncertainty are largely driven by projected changes in precipitation, particularly across south Asia. Figure 3-4 shows the average percentage change in average annual runoff for an increase in global average temperature of 2^{o}C above the 1980-2010 mean, averaged across five CMIP5 climate models and 11 hydrological models. The pattern of change in Figure 3-4 is different in some regions from the pattern shown in WGI Chapter 12 (Figure 12-24), largely because it is based on fewer climate models.

[INSERT FIGURE 3-4 HERE
Figure 3-4: Percentage change of mean annual streamflow for a global mean temperature rise of 2°C above 1980–2010 (2.7°C above pre-industrial). Color hues show the multi-model mean change across 4 GCMs and 11 global hydrological models (GHMs), and saturation shows the agreement on the sign of change across all 55 GHM-GCM combinations (percentage of model runs agreeing on the sign of change) (Schewe *et al*., 2013).]

The seasonal distribution of change in streamflow varies primarily with the seasonal distribution of change in precipitation, which in turn varies between scenarios. Figure 3-5 illustrates this variability, showing the percentage change in monthly average runoff in a set of catchments from different regions using scenarios from seven climate models, all scaled to represent a 2^{o}C increase in global mean temperature above the 1961-1990 mean. One of the climate models is separately highlighted, and for that model the figure also shows changes with a 4^{o}C rise in temperature. In the Mitano catchment in Uganda, for example, there is a non-linear relationship between amount of climate change and hydrological response. Incorporating uncertainty in hydrological model structure (Section 3.4.1) would increase further the range in projected impacts at the catchment scale.

[INSERT FIGURE 3-5 HERE
Figure 3-5: Change in mean monthly runoff across seven climate models in seven catchments, with a 2ºC increase in global mean temperature above 1961-1990 (Arnell, 2011; Hughes *et al*., 2011; Kingston and Taylor, 2010; Kingston *et al*., 2011; Nobrega *et al*., 2011; Thorne, 2011; Xu *et al*., 2011). One of the seven climate models (HadCM3) is highlighted separately, showing changes with both a 2ºC increase (dotted line) and a 4ºC increase (solid line).]

There is a much more consistent pattern of future seasonal change in areas 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.

3.4.5. Groundwater

While the relation between groundwater and climate change was rarely investigated before 2007, the number of studies and review papers (Green *et al*., 2011; Taylor R. *et al*., 2013a) has increased significantly since then. Ensemble studies, relying on between four and twenty climate models, of the impact of climate change on groundwater recharge and partially also on groundwater levels were done for the globe (Portmann *et al*., 2013), all of Australia (Crosbie *et al*., 2013a), the German Danube basin (Barthel *et al*., 2010), aquifers in Belgium and England (Goderniaux *et al*., 2011; Jackson *et al*., 2011), the Pacific coast of the USA and Canada (Allen *et al*., 2010) and the semi-arid High Plains aquifer of the USA (Crosbie *et al*., 2013b; Ng *et al*., 2010). With three exceptions, simulations were run under only one GHG emissions scenario. The range over the climate models of projected groundwater changes was large, from significant decreases to significant increases for the individual study areas, and the range of percentage changes of projected groundwater recharge mostly exceeded the range of projected precipitation changes. The uncertainties in projected groundwater recharge that originate in the hydrological models have not yet been explored. There are only a few studies of the impacts on groundwater of vegetation changes in response to climate change and CO_2 increase (Box CC-VW). Nor are there any studies on the impact of climate-driven changes of land use on groundwater recharge, even though projected increases in precipitation and streamflow variability due to climate change are expected to lead to increased groundwater abstraction (Taylor R. *et al*., 2013a), lowering groundwater levels and storage.

Under any particular climate scenario, the areas where total runoff (sum of surface runoff and groundwater recharge) is 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 the fraction of total runoff that recharges groundwater. Increased precipitation intensity may decrease groundwater recharge due to exceedance of the infiltration capacity (typically in humid areas), or may increase it due to faster percolation through the root zone and thus reduced evapotranspiration (typically in semi-arid areas) (Liu, 2011; Taylor R. *et al*., 2013b). The sensitivity of groundwater recharge and levels to climate change is diminished by perennial vegetation, fine-grained soils and aquitards, and is enhanced by annual cropping, sandy soils and unconfined (water-table) aquifers (Crosbie *et al*., 2013b; van Roosmalen *et al*., 2007). The sensitivity of groundwater recharge change to precipitation change was found to be highest for low groundwater recharge and lowest for high groundwater recharge, the ratio of recharge change to precipitation change ranging from 1.5 to 6.0 in the semi-arid High Plains aquifer (Crosbie *et al*., 2013b). 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).

Climate change affects coastal groundwater not only through changes in groundwater recharge but also through 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, unconfined aquifers are expected to suffer from saltwater intrusion (Werner *et al*., 2012). The volume available for freshwater storage is reduced if the water table cannot rise freely as the sea level rises (Masterson and Garabedian, 2007; Werner *et al*., 2012). This happens where land surfaces are low-lying, for example on many coral islands and in deltas, but also where groundwater discharges to streams. If the difference between the groundwater table and sea level is decreased by 1 meter, the thickness of the unconfined freshwater layer decreases by roughly 40 meter (Ghyben-Herzberg relation). Deltas are also affected by storm surges that drive salt water into stream channels, contaminating the underlying fresh groundwater from above (Masterson and Garabedian, 2007). In three modeling studies, the impact of sea-level rise on groundwater levels was found to be restricted to areas within 10 km from the coast (Carneiro *et al*., 2010; Oude Essink *et al*., 2010; Yechieli *et al*., 2010). Salt water intrusion due to sea-level rise is mostly a very slow process that may take several centuries to reach equilibrium (Webb and Howard, 2011). Even small rates of groundwater pumping from coastal aquifers are expected to lead to stronger salinization of the groundwater than sea-level rise during the 21st century (Ferguson and Gleeson, 2012; Loaiciga *et al*., 2012).

Changes in groundwater recharge also affect streamflow. In the Mitano basin in Uganda, mean global temperature increases of 4°C or more with respect to 1961-1990 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; Figure 3-5). Changing groundwater tables affect land-surface energy fluxes, including evaporation, and thus feed back on the climate system, in particular in semi-arid areas where the groundwater table is within 2-10 meter of the surface (Ferguson and Maxwell, 2010; Jiang *et al*., 2009).

3.4.6. Water Quality

Climate change affects the quality of water through a complex set of natural and anthropogenic mechanisms working concurrently in parallel and in series. Projections under climate-change scenarios are difficult, both to perform and interpret, because they require not only integration of the climate models with those used to analyze the transportation and transformation of pollutants in water, soil, and air but also the establishment of a proper baseline (Andersen *et al*., 2006; Arheimer *et al*., 2005; Bonte and Zwolsman, 2010; Ducharne, 2008; Marshall and Randhir, 2008; Rehana and Mujumdar, 2012; Towler *et al*., 2010; Trolle *et al*., 2011; Wilby *et al*., 2006). The models have different spatial scales and have to be adapted and calibrated to local conditions for which adequate and appropriate information is needed. In consequence, there are few projections of the impacts of climate change on water quality; where available, their uncertainty is high. It is evident, however, that water-quality projections depend strongly on (a) local conditions; (b) climatic and environmental assumptions; and (c) the current or reference pollution state (Bonte and Zwolsman, 2010; Chang, 2004; Kundzewicz and Krysanova, 2010; Sahoo *et al*., 2010; Trolle *et al*., 2011; Whitehead *et al*., 2009a; 2009b). Most projections suggest that future negative impacts will be similar in kind to those already observed in response to change and variability in air and water temperature, precipitation and storm runoff, and to many confounding anthropogenic factors (Chang, 2004; Whitehead *et al*., 2009a). This holds for natural and artificial reservoirs (Bonte and Zwolsman, 2010; Brikowski, 2008; Ducharne, 2008; Loos *et al*., 2009; Marshall and Randhir, 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 (Butscher and Huggenberger, 2009; Rozemeijer *et al*., 2009).

3.4.7. Soil Erosion and Sediment Load

Heavy rainfalls are *likely* to become more intense and frequent during the 21st century in many parts of the world (Seneviratne *et al*., 2012; WGI Chapter 11), which may lead to more intense soil erosion even if the total rainfall does not increase. At the global scale, soil erosion simulated assuming doubled CO_2 is projected to increase about 14% by the 2090s, compared to the 1980s (9% attributed to climate change and 5% to land use change), with increases by as much as 40-50% in Australia and Africa (Yang *et al*., 2003). The largest increases are expected in semiarid areas, where a single event may contribute 40% of total annual erosion (Bussi *et al*., 2013). In agricultural lands in temperate regions, soil erosion may respond to more intense erosion in complex non-linear ways; for instance in the UK a 10% increase in winter rainfall (i.e. during early growing season) could increase annual erosion of arable land by up to 150% (Favis-Mortlock and Boardman, 1995), while in Austria a simulation for 2010–2099 projected a decrease of rainfall by 10-14% in erosion-sensitive months and thus a decline in soil erosion by 11-24% (Scholz *et al*., 2008). Land management practices are critical for mitigating soil erosion under projected climate change. In China's Loess Plateau, four GCMs coupled to an erosion model show soil erosion increasing by 5-195% during 2010-2039 under conventional tillage, for three emission scenarios (A2, B2 and GGa), whereas under conservation tillage they show decreases of 26-77% (Li *et al*., 2011).

Climate change will also affect the sediment load in rivers by altering water discharge and land cover. For example, an increase in water discharge of 11-14% in two Danish rivers under the SRES A2 emission scenario was projected to increase the annual suspended sediment load by 9–16% during 2071-2100 (Thodsen *et al*., 2008). Increases in total precipitation, increased runoff from glaciers, permafrost degradation, and the shift of precipitation from snow to rain will further increase soil erosion and sediment loads in colder regions (Lu *et al*., 2010). In a major headwater basin of the Ganges River, increased precipitation and glacier runoff are projected to increase sediment yield by 26% by 2050 (Neupane and White, 2010). In the tropics, the intensity of cyclones is projected to increase 2-11% by 2100, which may increase soil erosion and landslides (Knutson *et al*., 2010).

In summary, projected increases in heavy rainfall and temperature will lead to changes in soil erosion and sediment load, but due to the non-linear dependence of soil erosion on rainfall rate and its strong dependence on land cover there is *low confidence* in projected changes in erosion rates. At the end of the 21st century, the impact of climate change on soil erosion is expected to be twice the impact of land-use change (Yang *et al*., 2003), although management practices may mitigate the problem at catchment scale.

3.4.8. Extreme Hydrological Events (Floods and Droughts)

The SREX report (Seneviratne *et al*., 2012) recognized that projected increases in temperature and heavy precipitation imply regional-scale changes in flood frequency and intensity, but with *low confidence* because these projections were obtained from a single GCM. Global flood projections based on multiple CMIP5 GCM simulations coupled with global hydrology and land surface models (Dankers *et al*., 2013; Hirabayashi *et al*., 2013) show flood hazards increasing over about half of the globe, but with great variability at the catchment scale. Projections of increased flood hazard are consistent for parts of south and southeast Asia, tropical Africa, northeast Eurasia, and South America (Figure 3-6), while decreases are projected in parts of northern and eastern Europe, Anatolia, central Asia, central North America, and southern South America. This spatial pattern resembles closely that described by Seneviratne *et al.* (2012), but the latest projections justify *medium confidence* despite new appreciation of the large uncertainty due to variation between climate models and their coupling to hydrological models.

[INSERT FIGURE 3-6 HERE
Figure 3-6: a) Multi-model median return period (years) in the 2080s for the 20th-century 100-year flood (Hirabayashi *et al*., 2013), based on one hydrological model driven by 11 CMIP5 GCMs under RCP8.5. At each location the magnitude of the 100-year flood was estimated by fitting a Gumbel distribution function to time series of simulated annual maximum daily discharge in 1971–2000, and the return period of that flood in 2071–2100 was estimated by fitting the same distribution to discharges simulated for that period. b) Global exposure to the 20th-century 100-year flood (or greater) in millions of people (Hirabayashi *et al*., 2013). Left: ensemble means of historical (black thick line) and future simulations (coloured thick lines) for each scenario. Shading denotes ±1 standard deviation. Right: maximum and minimum (whiskers), mean (horizontal thick lines within each bar), ±1 standarddeviation (box) and projections of each GCM (coloured symbols) averaged over the 21st century. The impact of 21st-century climate change is emphasized by fixing the population to that of 2005. Annual global flood exposure increases over the century by 4-14 times as compared to the 20th century [4±3 (RCP2.6), 7±5 (RCP4.5), 7±6 (RCP6.0) and 14±10 (RCP8.5) times, or 0.1% to 0.4-1.2% of the global population in 2005)]. Under a scenario of moderate population growth (UN, 2011), the global number of exposed people is projected to increase by a factor of 7-25, depending on the RCP, with strong increases in Asia and Africa due to high population growth.]

There have been several assessments of the potential effect of climate change on meteorological droughts (less rainfall) and agricultural droughts (drier soil) (e.g. WGI Chapter 12; Orlowsky and Seneviratne, 2013; Vidal *et al*., 2012), but few on hydrological droughts, either in terms of river runoff or groundwater levels. Many catchment-scale studies (Section 3.4.4) consider changes in indicators of low river flow (such as the flow exceeded 95% of the time), but these indicators do not necessarily characterise 'drought' as they define neither duration nor spatial extent, and are not necessarily particularly extreme or rare. In an ensemble comparison under SRES A1B of the proportion of the land surface exhibiting significant projected changes in hydrological drought frequency to the proportions exhibiting significant changes in meteorological and agricultural drought frequency, 18-30% of the land surface (excluding cold areas) experienced a significant increase in the frequency of 3-month hydrological droughts, whilst approximately 15-45% saw a decrease (Taylor I. *et al*., 2013). This is a smaller area with increased frequency, and a larger area with decreased frequency, than for meteorological and agricultural droughts, and is understandable because river flows reflect the accumulation of rainfall over time. Flows during dry periods may be sustained by earlier rainfall. For example at the catchment scale in the Pacific Northwest (Jung and Chang, 2012), short hydrological droughts are projected to increase in frequency whilst longer droughts remain unchanged because, although dry spells last longer, winter rainfall increases.

The impacts of floods and droughts are projected to increase even when the hazard remains constant, due to increased exposure and vulnerability (Kundzewicz *et al*., 2013). Projected flood damages vary greatly between models and from region to region, with the largest losses in Asia. Projections from 21 GCMs under SRES A1B of the population exposed by 2050 to a doubling of flood frequency range from 31 to 449 million people, and the change in risk varies between -9 and +376% (Arnell and Gosling, 2013). Studies of projected flood damages are mainly focussed in Europe, the USA and Australia (Bouwer, 2013; Handmer *et al*., 2012). In Europe, the annual damage (€6.4 billion) and number of people exposed (200,000) in 1961-1990 are expected to increase about twofold by the 2080s under scenario B2 and about three times under scenario A2 (Feyen *et al*., 2012). Drought impacts at continental and smaller scales are difficult to assess because they will vary greatly with the local hydrological setting and water-management practices (Handmer *et al*., 2012). More frequent droughts due to climate change may challenge existing water management systems (Kim *et al*., 2009); together with an increase of population, this may place at risk even the domestic supply in parts of Africa (MacDonald *et al*., 2009).

3.5. Projected Impacts, Vulnerabilities, and Risks

In general, projections of freshwater-related impacts, vulnerabilities and risks caused by climate change are evaluated by comparison to historical conditions. Such projections are helpful 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 the different hydrological changes that are projected under different future GHG emissions scenarios, or different amounts of global mean temperature rise. One objective of such projections is to quantify what may happen under current water-resources management practice, and another is to indicate what actions may be needed to avoid undesirable outcomes (Oki and Kanae, 2006). The studies compiled in Table 3-2 illustrate the benefits of reducing GHG emissions for the Earth's freshwater systems. Emissions scenarios are rather similar until the 2050s. Their impacts, and thus the benefits of mitigation, tend to become more clearly marked by the end of the 21st century. For example, the fraction of the world population exposed to a 20th century 100-year flood is projected to be, at the end of the 21st century, three times higher per year for RCP8.5 than for RCP2.6 (Hirabayashi *et al*., 2013). Each degree of global warming (up to 2.7°C above pre-industrial levels; Schewe *et al.*, 2013) is projected to decrease renewable water resources by at least 20% for an additional 7% of the world population. The number of people with significantly decreased access to renewable groundwater resources is projected to be roughly 50% higher under RCP8.5 than under RCP2.6 (Portmann *et al*., 2013). The percentage of global population living in river basins with new or aggravated water scarcity is projected to increase with global warming, from 8% at 2°C to 13% at 5°C (Gerten *et al.*, 2013).

[INSERT TABLE 3-2 HERE
Table 3-2: Effects of different GHG emissions scenarios on hydrological changes and freshwater-related impacts of climate change on humans and ecosystems. Among the SRES scenarios, GHG emissions are highest in A1f and A2, lower in A1 and B2, and lowest in B1. RCP8.5 is similar to A2, while the lower emissions scenarios RCP6.0 and RCP4.5 are similar to B1. RCP2.6 is a very low emissions scenario (Figure 1-4 and Section 1.1.3.1 in Chapter 1). The studies in the table give global warming (GW: global mean temperature rise, quantified as the CMIP5 model

mean) over different reference periods, typically since pre-industrial. GW is projected to be, for RCP8.5, approximately 2°C in the 2040s and 4°C in the 2080s. For RCP6.0, GW is 2°C in the 2060s and 2.5°C in the 2080s, while in RCP2.6, GW stays below 1.8°C throughout the 21st century (Figure 1-4 in Chapter 1). Population scenario SSP2 assumes a medium population increase.]

3.5.1. Availability of Water Resources

Approximately 80% of the world's population already suffers serious threats to its water security, as measured by indicators including water availability, water demand and pollution (Vörösmarty *et al*., 2010). Climate change can alter the availability of water and therefore threaten 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*., 2011; Arnell *et al*., 2013; Fung *et al*., 2011; Gerten *et al*., 2013; Gosling and Arnell, 2013; Hayashi *et al*., 2010; Murray *et al*., 2012; Schewe *et al*., 2013), whilst others have projected future human withdrawals and characterized availability by the ratio of withdrawals to availability from runoff or recharge (Arnell *et al*., 2011; Gosling and Arnell, 2013; Hanasaki *et al*., 2013). A groundwater vulnerability index was constructed which combined future reductions of renewable groundwater resources with water scarcity, dependence on groundwater and the Human Development Index (Figure 3-7) (Döll, 2009). 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 between climate models, and strongly with the pattern of projected rainfall change. There is strong consistency in projections of reduced availability around the Mediterranean and parts of southern Africa, but much greater variation in projections for south and east Asia. Second, some water-stressed areas see increased runoff in the future (Section 3.4.4), and therefore less exposure to water-resources stress. Third, over the next few decades and for increases in global mean temperature of less than around 2^{o}C above pre-industrial, changes in population will generally have a greater effect on changes in resource availability than will climate change. Climate change would, however, regionally exacerbate or offset the effects of population pressures. Fourth, estimates of future water availability are sensitive not only to climate and population projections and population assumptions, but also to the choice of hydrological impact model (Schewe *et al*., 2013) and to the adopted measure of stress or scarcity. As an indication of the potential magnitude of the impact of climate change, Schewe *et al*. (2013) estimated that approximately 8% of the global population would see a severe reduction in water resources (a reduction in runoff either greater than 20% or more than the standard deviation of current annual runoff) with a 1^{o}C rise in global mean temperature (compared to the 1990s), rising to 14% at 2^{o}C and 17% at 3^{o}C; the spread across climate and hydrological models was, however, large.

[INSERT FIGURE 3-7 HERE
Figure 3-7: Human vulnerability to climate-change induced decreases of renewable groundwater resources by the 2050s. Lower (B2) and higher (A2) emissions pathways are interpreted by two global climate models. The higher the vulnerability index (computed by multiplying percentage decrease of groundwater recharge by a sensitivity index), the higher the vulnerability. The index is only defined for areas where groundwater recharge is projected to decrease by at least 10% relative to 1961-1990 (Döll, 2009)]

Under climate change, reliable surface water supply is expected to decrease due to increased variability of river flow that is due in turn to increased precipitation variability and decreased snow and ice storage. Under these circumstances, it might be beneficial to take advantage of the storage capacity of groundwater and to increase groundwater withdrawals (Kundzewicz and Döll, 2009). However, this option is only sustainable where, over the long term, withdrawals remain well below recharge, while care must also be taken to avoid excessive reduction of groundwater outflow to rivers. Therefore, groundwater cannot be expected to ease freshwater stress 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 of more than 10% between the 1980s and the 2080s was computed to range from 24% (mean based on five GCMs, range 11-39%) for RCP2.6 to 38% (range 27-50%) for RCP8.5 (Portmann *et al*., 2013; Table 3-2). The land area affected by decreases of groundwater resources increases linearly with global mean temperature rise between 0°C and 3°C. For each degree of global mean temperature rise, an additional 4% of the global land area is projected to suffer a groundwater resources decrease of more than 30%, and an additional 1% to suffer a decrease of more than 70% (Portmann *et al*., 2013).

3.5.2. Water Uses

3.5.2.1. Agriculture

Water demand and use for food and livestock feed production is governed not only by crop management and its efficiency, but also by the balance between atmospheric moisture deficit and soil water supply. Thus, changes in climate (precipitation, temperature, radiation) will affect the water demand of crops grown in both irrigated and rainfed systems. Using projections from 19 CMIP3 GCMs forced by SRES A2 emissions to drive a global vegetation and hydrology model, climate change by the 2080s would hardly alter the global irrigation water demand of major crops in areas currently equipped for irrigation (Konzmann *et al.*, 2013). However, there is *high confidence* that irrigation demand will increase significantly in many areas (by more than 40% across Europe, the USA and parts of Asia). Other regions – including major irrigated areas in India, Pakistan and southeastern China – might experience a slight decrease in irrigation demand, due for example to higher precipitation, but only under some climate change scenarios (also see Biemans *et al.*, 2013). Using seven global hydrological models but a limited set of CMIP5 projections, Wada *et al.* (2013) suggested a global increase in irrigation demand by the 2080s (ensemble average 7–21% depending on emissions scenario), with a pronounced regional pattern, a large inter-model spread, and possible seasonal shifts in crop water demand and consumption. By contrast, based on projections from two GCMs and two emissions scenarios, a slight global decrease in crop water deficits was suggested in both irrigated and rainfed areas by the 2080s, which can partly be explained by a smaller difference between daily maximum and minimum temperatures (Zhang and Cai, 2013). As in other studies, region-to-region variations were very heterogeneous.

Where poor soil is not a limiting factor, physiological and structural crop responses to elevated atmospheric CO_2 concentration (CO_2 fertilization) might partly cancel out the adverse effects of climate change, potentially reducing global irrigation water demand (Konzmann *et al.*, 2013; Box CC-VW). However, even in this optimistic case, increases in irrigation water demand by >20% are still projected under most scenarios for some regions, such as southern Europe. In general, future irrigation demand is projected to exceed local water availability in many places (Wada *et al.*, 2013). The water demand to produce a given amount of food on either irrigated or rainfed cropland will increase in many regions due to climate change alone (Gerten *et al.*, 2011, projections from 17 CMIP3 GCMs, SRES A2 emissions), but this increase might be moderated by concurrent increases in crop water productivity due to CO_2 effects, i.e. decreases in per-calorie water demand. The CO_2 effects may thus lessen the global number of people suffering water scarcity; nonetheless, the effect of anticipated population growth is *likely* to exceed those of climate and CO_2 change on agricultural water demand, use, and scarcity (Gerten *et al.*, 2011).

Rainfed agriculture is vulnerable to increasing precipitation variability. Differences in yield and yield variability between rainfed and irrigated land may increase with changes in climate and its variability (e.g. Finger *et al.*, 2011). Less irrigation water might be required for paddy rice cultivation in monsoon regions where rainfall is projected to increase and the crop growth period to become shorter (Yoo *et al*., 2013). Water demand for rainfed crops could be reduced by better management (Brauman *et al.*, 2013), but unmitigated climate change may counteract such efforts, as shown in a global modelling study (Rost *et al.*, 2009). In some regions, expansion of irrigated areas or increases of irrigation efficiencies may overcome climate change impacts on agricultural water demand and use (McDonald and Girvetz, 2013).

3.5.2.2. Energy Production

Hydroelectric and thermal power plants, and the irrigation of bioenergy crops (Box CC-WE), require large amounts of water. This section assesses the impact of hydrological changes (as described in Section 3.4) on hydroelectric and thermal power production. The impacts of changes in energy production due to climate change mitigation efforts are discussed in Section 3.7.2.1, while the economic implications of the impact of climate change on thermal power and hydropower production as well as adaptation options are assessed in Chapter 10.

Climate change affects hydropower generation through changes in the mean annual streamflow, shifts of seasonal flows and increases of streamflow variability (including floods and droughts) as well as by increased evaporation from reservoirs and changes in sediment fluxes. Therefore, the impact of climate change on a specific hydropower plant will depend on the local change of these hydrological characteristics, as well as on the type of hydropower plant and on the (seasonal) energy demand, which will itself be affected by climate change (Golombek *et al*., 2012). Run-of-river power plants are more susceptible to increased flow variability than plants at dams. Projections of future hydropower generation are subject to the uncertainty of projected precipitation and streamflow. For example, projections to the 2080s of hydropower generation in the Pacific Northwest of the USA range from a decrease of 25% to an increase of 10% depending on the climate model (Markoff and Cullen, 2008). Based on an ensemble of 11 GCMs, hydropower generation at the Aswan High Dam (Egypt) was computed to remain constant until the 2050s but to decrease, following the downward trend of mean annual river discharge, to 90% (ensemble mean) of current mean annual production under both SRES B1 and A2 (Beyene *et al*., 2010; Table 3-2). In snow-dominated basins, increased discharge in winter, smaller and earlier spring floods and reduced discharge in summer have already been observed (Section 3.2.5) and there is *high confidence* that these trends will continue. In regions with high electricity demands for heating, this makes the annual hydrograph more similar to seasonal variations in electricity demand, reducing required reservoir capacities and providing opportunities for operating dams and power stations to the benefit of riverine ecosystems (Golombek *et al*., 2012; Renofalt *et al*., 2010). In regions with high electricity demand for summertime cooling, however, this seasonal streamflow shift is detrimental. In general, climate change requires adaptation of operating rules (Minville *et al*., 2009; Raje and Mujumdar, 2010) which may, however, be constrained by reservoir capacity. In California, for example, high-elevation hydropower systems with little storage, which rely on storage in the snowpack, are projected to yield less hydropower due to the increased occurrence of spills, unless precipitation increases significantly (Madani and Lund, 2010). Storage capacity expansion would help increase hydropower generation but might not be cost-effective (Madani and Lund, 2010).

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, due to increases in stream temperatures and the incidence of low flows (Flörke *et al*., 2012; van Vliet *et al*., 2012; Table 3-2). Warmer cooling water was computed to lower thermal power plant efficiency and thus electricity production by 1.5-3% in European countries by the 2080s under emissions scenario A1b (Golombek *et al*., 2012).

3.5.2.3. Municipal Services

Under climate change, 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, 2008; Major *et al*., 2011; Mukhopadhyay and Dutta, 2010; Qin *et al*., 2010; Thorne and Fenner, 2011; van Vliet and Zwolsman, 2008; Whitehead *et al*., 2009a):

- Higher ambient temperatures, which reduce snow and ice volumes and increase the evaporation rate from lakes, reservoirs and aquifers. These changes decrease natural storage of water and hence, unless precipitation increases, its availability. Moreover, higher ambient temperatures increase water demand, and with it the competition for the resource (*medium to high agreement, limited evidence*).
- Shifts in timing of river flows and possible more frequent or intense droughts, which increase the need for artificial water storage.
- Higher water temperatures, which encourage algal blooms and increase risks from cyanotoxins and natural organic matter in water sources, requiring additional or new treatment of drinking water (*high agreement, medium evidence*). On the positive side, biological water and wastewater treatment is more efficient when the water is warmer (Tchobanoglous *et al*., 2003).
- Possibly drier conditions, which increase pollutant concentrations. This is a concern especially for groundwater sources that are already of low quality, even when pollution is natural as in India and Bangladesh, North and Latin America and Africa; here arsenic, iron, manganese and fluorides are often a problem (Black and King, 2009).

- Increased storm runoff, which increases loads of pathogens, nutrients and suspended sediment.
- Sea-level rise, which increases the salinity of coastal aquifers, in particular where groundwater recharge is also expected to decrease.

Climate change also impacts water quality indirectly. For instance, at present many cities rely on water from forested catchments that requires very little treatment. More frequent and severe forest wildfires could seriously degrade water quality (Emelko *et al*., 2011; Smith *et al*., 2011).

Many drinking-water treatment plants – especially small ones – are not designed to handle the more extreme influent variations that are to be expected under climate change. These demand additional or even different infrastructure capable of operating for up to several months per year, which renders wastewater treatment very costly, notably in rural areas (Arnell *et al*., 2011; Zwolsman *et al*., 2010).

Sanitation technologies vary in their resilience to climate impacts (Howard *et al*., 2010). For sewage, three climatic conditions are of interest (NACWA, 2009; Zwolsman *et al*., 2010):

- Wet weather: heavier rainstorms mean increased amounts of water and wastewater in combined systems for short periods. Current designs, based on critical "design storms" defined through analysis of historical precipitation data, therefore need to be modified. New strategies to adapt to and mitigate urban floods need to be developed, considering not only climate change but also urban design, land use, the "heat island effect" and topography (Changnon, 1969).
- Dry weather: soil shrinks as it dries, causing water mains and sewers to crack and making them vulnerable to infiltration and exfiltration of water and wastewater. The combined effects of higher temperatures, increased pollutant concentrations, longer retention times, and sedimentation of solids may lead to increasing corrosion of sewers, shorter asset lifetimes, more drinking-water pollution and higher maintenance costs.
- Sea-level rise: intrusion of brackish or salty water into sewers necessitates processes that can handle saltier wastewater.

Increased storm runoff implies the need to treat additional wastewater when combined sewers are used, as storm runoff adds to sewage; in addition, the resulting mixture has a higher content of pathogens and pollutants. Under drier conditions higher concentrations of pollutants in wastewater, of any type, are to be expected and must be dealt with (Whitehead *et al*., 2009a; 2009b; Zwolsman *et al*., 2010). The cost may rule this out in low-income regions (Chakraborti *et al*., 2011; Jiménez, 2011). The disposal of wastewater or faecal sludge is a concern that is just beginning to be addressed in the literature (Seidu *et al*., 2013).

3.5.2.4. Freshwater Ecosystems

Freshwater ecosystems are comprised of biota (animals, plants and other organisms) and their abiotic environment in slow-flowing surface waters such as lakes, man-made reservoirs or wetlands; in fast-flowing surface waters such as rivers and creeks; and in the groundwater. They have suffered more strongly from human activities than have marine and 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 (Millennium Ecosystem Assessment, 2005). Climate change is an additional stressor of freshwater ecosystems, which it affects not only through increased water temperatures (discussed in Chapter 4.3.3.3) but also by altered streamflow regimes, river water levels, and extent and timing of inundation (Box CC-RF). Wetlands in dry environments are hotspots of biological diversity and productivity, and their biotas are at risk of extinction if runoff decreases and the wetland dries out (as described for Mediterranean-type temporary ponds by Zacharias and Zamparas, 2010). Freshwater ecosystems are also affected by water quality changes induced by climate change (Section 3.2.5), and by human adaptations to climate-change induced increases of streamflow variability and flood risk, such as the construction of dykes and dams (Ficke *et al*., 2007; Section 3.7.2).

3.5.2.5. Other Uses

In addition to direct impacts, vulnerabilities and risks in water-related sectors, indirect impacts of hydrological changes are expected for navigation, transportation, tourism, and urban planning (Badjeck *et al*., 2010; Beniston, 2012; Koetse and Rietveld, 2009; Pinter *et al*., 2006; Rabassa, 2009). Social and political problems can result from hydrological changes. For example, water scarcity and water overexploitation may 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). Snowline rise and glacier shrinkage are *very likely* to impact environmental, hydrological, geomorphological, heritage, and tourism resources in cold regions (Rabassa, 2009), as already observed for tourism in the European Alps (Beniston, 2012). While most impacts will be adverse, some might be beneficial.

3.6. Adaptation and Managing Risks

In the face of hydrological changes and freshwater-related impacts, vulnerability and risks due to climate change, there is need for adaptation and for increasing resilience. Managing the changing risks due to the impacts of climate change is the key to adaptation in the water sector (IPCC, 2012), and risk management should be part of decision making and the treatment of uncertainty (ISO, 2009). Even to exploit the positive impacts of climate change on freshwater systems, adaptation is generally required.

3.6.1. Options

There is growing agreement that an adaptive approach to water management can successfully address uncertainty due to climate change. Although there is *limited evidence* of the effectiveness of such an approach, the evidence is growing (Section 3.6.2). Many practices identified as adaptive were originally reactions to climate variability. Climate change provides many opportunities for “low-regret” solutions, capable of yielding social and/or economic benefits and adaptive both to variability and to change (Table 3-3). Adaptive techniques include scenario planning, experimental approaches that involve learning from experience, and the development of flexible solutions that are resilient to uncertainty. A programme of adaptation typically mixes “hard” infrastructural and “soft” institutional measures (Bates *et al*., 2008; Cooley, 2008; Mertz *et al*., 2009; Olhoff and Schaer, 2010; Sadoff and Muller, 2009; UNECE, 2009).

[INSERT TABLE 3-3 HERE
Table 3-3: Categories of climate change adaptation options for the management of freshwater resources.
A+M: may assist both adaptation and mitigation
(1)This includes water reuse, rain water harvesting, and desalination, among others.
With information from: Arkell (2011a; 2011b); Andrews (2009); Bahri (2009); Bowes *et al*. (2012); de Graaf and der Brugge (2010); Dembo (2010); Dillon and Jiménez (2008); Elliott *et al*. (2011); Emelko *et al*. (2011); Godfrey *et al*. (2010); Howard *et al*. (2010); Jiménez and Asano (2008); Jiménez (2011); Keller (2008); Kingsford (2011); Mackay and Last (2010); Major *et al*. (2011); Marsalek *et al*. (2006); McCafferty (2008); McGuckin (2008); Mogaka *et al*. (2006); Mukhopadhyay and Dutta (2010); Munasinghe (2009); 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); Wang X. *et al*. (2011); Whitehead *et al*. (2009b); Zwolsman *et al*. (2010)]

To avoid adaptation that goes wrong – “maladaptation” – scientific research results should be analyzed during planning. Low-regret solutions, such as those for which moderate investment clearly increases the capacity to cope with projected risks or for which the investment is justifiable under all or almost all plausible scenarios, should be considered explicitly. Involving all stakeholders, reshaping planning processes, coordinating the management of land and water resources, recognizing linkages between water quantity and quality, using surface water and groundwater conjunctively, and protecting and restoring natural systems, are examples of principles that can beneficially inform planning for adaptation (World Bank, 2007).

Integrated Water Resource Management continues to be a promising instrument for exploring adaptation to climate change. It can be joined with a Strategic Environmental Assessment to address broader considerations. Attention is currently increasing to "robust measures" (European Communities, 2009), which are measures that perform well under different future conditions and clearly optimize prevailing strategies (Sigel *et al.*, 2010). Barriers to adaptation are discussed in detail in Section 16.5 in Chapter 16. Barriers to adaptation in the freshwater sector include lack of human and institutional capacity, lack of financial resources, lack of awareness, and lack of communication (Browning-Aiken *et al*., 2007; Burton, 2008; Butscher and Huggenberger, 2009; Zwolsman *et al*., 2010). Institutional structures can be major barriers to adaptation (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); structures that promote participation of and collaboration between stakeholders tend to encourage adaptation. Some adaptation measures may not pass the test of workability in an uncertain future (Campbell *et al.*, 2008), and uncertainty (Section 3.6.2) can be another significant barrier.

Case studies of the potential effectiveness of adaptation measures are abundant. Changes in operating practices and infrastructure improvements could help California's water managers respond to changes in the volume and timing of supply (Connell-Buck *et al*., 2011; Medellin-Azuara *et al*., 2008). Other studies include evaluations of the effectiveness of different adaptation options in Washington state, USA (Miles *et al*., 2010) and the Murray-Darling basin, Australia (Pittock and Finlayson, 2011), and of two dike-heightening strategies in the Netherlands (Hoekstra and de Kok, 2008). Such studies have demonstrated that it is technically feasible in general to adapt to projected climate changes, but not all have considered how adaptation would be implemented.

3.6.2. Dealing with Uncertainty in Future Climate Change

One of the key challenges in factoring climate change into water resources management lies in the uncertainty. Some approaches (e.g. in England and Wales, Arnell, 2011) use a small set of climate scenarios to characterise the potential range of impacts on water resources and flooding. Others (e.g. Brekke *et al*., 2008; Christierson *et al*., 2012; Hall *et al*., 2012; Lopez *et al*., 2009) use very large numbers of scenarios to generate likelihood distributions of indicators of impact for use in risk assessment. However, it has been argued (Dessai *et al*., 2009; Hall, 2007; Stainforth *et al*., 2007) that attempts to construct probability distributions of impacts are misguided because of "deep" uncertainty, which arises because analysts do not know, or cannot agree upon, how the climate system and water-management systems may change, how models represent possible changes, or how to value the desirability of different outcomes. Stainforth *et al*. (2007) therefore argue that it is impossible in practice to construct robust quantitative probability distributions of climate change impacts, and that climate change uncertainty needs to be represented differently, for example by using fewer plausible scenarios and interpreting the outcomes of scenarios less quantitatively.

Some go further, arguing that climate models are not sufficiently robust or reliable to provide the basis for adaptation (Anagnostopoulos *et al*., 2010; Blöschl and Montanari, 2010; Koutsoyiannis *et al*., 2008; Wilby, 2010), because they are frequently biased and do not reproduce the temporal characteristics (specifically the persistence or "memory") often found in hydrological records. It has been argued (Lins and Cohn, 2011; Stakhiv, 2011) that existing water-resources planning methods are sufficiently robust to address the effects of climate change. This view of climate model performance has been challenged and is the subject of some debate (Huard, 2011; Koutsoyiannis *et al*., 2009; 2011); the critique also assumes that adaptation assessment procedures would only use climate scenarios derived directly from climate model simulations.

Addressing uncertainty in practice by quantifying it through some form of risk assessment, however, is only one way of dealing with uncertainty. A large and increasing literature recommends that water managers should move from the traditional "predict and provide" approach towards adaptive water management (Gersonius *et al*., 2013; Huntjens *et al*., 2012; Matthews and Wickel, 2009; 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). Approaches that are resilient to uncertainty are not entirely technical (or supply-side), and participation and collaboration amongst all stakeholders are central to adaptive water management. However, whilst climate change is frequently cited as a key motive, there is very little published guidance on how to implement the adaptive water management approach. Some examples are given in Ludwig *et al*. (2009). The most comprehensive overview of adaptive water management which explicitly incorporates climate change and its uncertainty is the three-step framework of the US Water Utilities Climate Alliance (WUCA, 2010): system vulnerability assessment, utility planning using decision-support methods, and decision-making and implementation. Planning methods for decision support include classic decision analysis, traditional scenario planning and robust decision making (Lempert *et al*., 1996; 2006; Nassopoulos *et al*., 2012). The latter was applied by the Inland Empire Utilities Agency, supplying water to a region in southern California (Lempert and Groves, 2010). This led to the refinement of the company's water resource management plan, making it more robust to three particularly challenging aspects of climate change that were identified by the scenario analysis. Another framework, based on risk assessment, is the threshold-scenario framework of Freas *et al*. (2008).

3.6.3. Costs of Adaptation to Climate Change

Calculating the global cost of adaptation in the water sector is a difficult task and results are highly uncertain. Globally, to maintain water services at non-climate change levels to the year 2030 in more than 200 countries, total adaptation costs for additional infrastructure were estimated as US$531 billion, with US$451 billion (85%) required in developing countries, mainly in Asia and Africa (Kirshen, 2007). Including two further costs, for reservoir construction since the best locations have already been taken, and for unmet irrigation demands, total water-sector adaptation costs were estimated as US$225 billion, or US$11 billion per year (UNFCCC, 2007).

Average annual water-supply and flood-protection costs to 2050 for restoring service to non-climate change levels were estimated to be US$14.0 billion for a dry GCM projection of the SRES A2 scenario and US$19.7 billion for a wet GCM projection (World Bank, 2010; Ward *et al*., 2010). Annual urban infrastructure costs, primarily for wastewater treatment and urban drainage, were US$13.7 billion (dry) and US$27.5 billion (wet). Under both GCM projections for the A2 scenario, the water sector accounted for approximately 50% of total global adaptation cost, which was distributed regionally in the proportions: East Asia/Pacific, 20%; Europe/Central Asia, 10%; Latin America/Caribbean, 20%; Middle East/North Africa, 5%; South Asia, 20%; Sub-Saharan Africa, 20%.

Annual costs for adaptation to climate change in sub-Saharan Africa are estimated as US$1.1–2.7 billion for current urban water infrastructure, plus US$1.0–2.5 billion for new infrastructure to meet the 2015 Millennium Development Goals (Muller, 2007). These estimates assume a 30% reduction in stream flow and an increase of at least 40% in the unit cost of water. Annual estimates of adaptation costs for urban water storage are $0.15-0.5 billion for existing facilities and $0.55-1.5 billion for new developments. For wastewater treatment, the equivalent estimates are $0.1-0.2 billion and $0.075-0.2 billion. For the coterminous United States under "business as usual", over 45% of economic costs are due to water quality and environmental flow impacts, suggesting significant costs for wastewater treatment infrastructure (Henderson *et al.*, 2013).

3.6.4. Adaptation in Practice in the Water Sector

A number of water management 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. Most of the work has involved developing methodologies to be used by water resources and flood managers (e.g. Rudberg *et al*., 2012), and therefore represents attempts to improve adaptive capacity. In England and Wales, for example, methodologies to gauge the effects of climate change on reliability of water supplies have evolved since the late 1990s (Arnell, 2011) and the strategic plans of water supply companies now generally allow for climate change. Brekke *et al*. (2009a) describe proposed changes to practices in the USA. Several studies report community-level activities to reduce exposure to current hydrological variability, regarded explicitly 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).

[INSERT TABLE 3-4 HERE
Table 3-4: Key risks from climate change and the potential for reducing risk through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments by chapter authors, with evaluation of evidence and agreement in supporting chapter sections. Each key risk is characterized as very low to very high. Risk levels are presented in three time frames: the present, near-term (here assessed over 2030-2040), and longer term (here assessed over 2080-2100). Sources: Xie et al., 2006; Döll, 2009; Kaser et al., 2010; Arnell et al., 2011; Huss, 2011; Jóhannesson et al., 2012; Seneviratne et al., 2012; Arnell and Gosling, 2013; Dankers et al., 2013; Gosling and Arnell, 2013; Hanasaki et al., 2013; Hirabayashi et al., 2013; Kundzewicz et al., 2013; Portmann et al., 2013; Radić et al., 2013; Schewe et al., 2013; WGI AR5 Chapter 13.]

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, forestry and industry might have impacts on the freshwater system, and therefore needs to be considered while planning adaptation in the water sector (Jiang *et al.*, 2013). For example, better agricultural land management practices can also reduce erosion and sedimentation in river channels (Lu *et al.*, 2010), while controlled flooding of agricultural land can alleviate the impacts of urban flooding. Increased irrigation upstream may limit water availability downstream (World Bank, 2007). A project designed for other purposes may also deliver increased resilience to climate change as a co-benefit, even without a specifically identified adaptive component (World Bank, 2007; Falloon and Betts, 2010).

3.7.2. Climate Change Mitigation and Freshwater Systems

3.7.2.1. Impact of Climate Change Mitigation on Freshwater Systems

Many measures for climate change mitigation affect freshwater systems. Afforestation generally increases evapotranspiration and decreases total runoff (van Dijk and Keenan, 2007). Afforestation of areas deemed suitable according to the Clean Development Mechanism–Afforestation/Reforestation provisions of the Kyoto Protocol (7.5 million km^2) would lead to large and spatially-extensive 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 of 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 only because it pays less than 1% of the actual cost of streamflow reduction caused by replacing Fynbos by the plantations (Chisholm, 2010). In general, afforestation has beneficial impacts on soil erosion, local flood risk, water quality (nitrogen, phosphorus, suspended sediments) and stream habitat quality (Trabucco *et al*., 2008; van Dijk and Keenan, 2007; Wilcock *et al*., 2008).

Irrigated bioenergy crops and hydropower can have negative impacts on freshwater systems (Jacobson, 2009). In the USA, water use for irrigating biofuel crops could increase from 2% of total water consumption in 2005 to 9% in 2030 (King *et al*., 2010). Irrigating some bioenergy crops may cost more than the energy thus gained. In dry parts of India, pumping from a depth of 60 meter for irrigating jatropha is estimated to consume more energy than that gained from the resulting higher crop yields (Gupta *et al*., 2010). For a biofuel 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; biofuel production is projected to increase water consumption significantly in some countries (e.g. Germany, Italy and South Africa), and to exacerbate the already serious water scarcity in others (e.g. Spain and China) (Gerbens-Leenes *et al*., 2012). Conversion of native Caatinga forest into rainfed fields for biofuels in semi-arid northwestern Brazil may lead to a significant increase of groundwater recharge (Montenegro and Ragab, 2010), but there is a risk of soil salinization due to rising groundwater tables.

Hydropower generation leads to alteration of river flow regimes that negatively affect freshwater ecosystems, in particular biodiversity and abundance of riverine organisms (Döll and Zhang, 2010; Poff and Zimmerman, 2010), and to fragmentation of river channels by dams, with negative impacts on migratory species (Bourne *et al*., 2011). Hydropower operations often lead to discharge changes on hourly timescales that are detrimental to the downstream river ecosystem (Bruno *et al*., 2009; Zimmerman *et al*., 2010). However, release management and structural measures like fish ladders can mitigate these negative impacts somewhat (Williams, 2008). In tropical regions, the global warming potential of hydropower, due to methane emissions from man-made reservoirs, may exceed that of thermal power; based on observed emissions of a tropical reservoir, this might be the case where the ratio of hydropower generated to the surface area of the reservoir is less than 1 MW/km^2 (Gunkel, 2009).

CO_2 leakage to freshwater aquifers from saline aquifers used for carbon capture and storage (CCS) can lower pH by 1-2 units and increase concentrations of metals, uranium and barium (Little and Jackson, 2010). Pressure exerted by gas injection can push brines or brackish water into freshwater parts of the aquifer (Nicot, 2008). Displacement of brine into potable water was not considered in a screening methodology for CCS sites in the Netherlands (Ramírez *et al*., 2010). Another emergent freshwater-related risk of climate mitigation is increased natural gas extraction from low-permeability rocks. The required hydraulic fracturing process ("fracking") uses large amounts of water (a total of approximately 9,000-30,000 m^3 per well, mixed with a number of chemicals), of which a part returns to the surface (Rozell and Reaven, 2012). Fracking is suspected to lead to pollution of the overlying freshwater aquifer or surface waters, but appropriate observations and peer-reviewed studies are still lacking (Jackson *et al*., 2013). Densification of urban areas to reduce traffic emissions is in conflict with providing 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 because energy is required to pump and treat water, to heat it, and to treat wastewater. For example, water supply and water treatment were responsible for 1.4 % of total electricity consumption in Japan in 2008 (MLIT, 2011). In the USA, total water-related energy consumption was equivalent to 13% of total electricity production in 2005, with 70% for water heating, 14% for wastewater treatment and only 5% for pumping of irrigation water (Griffiths-Sattenspiel and Wilson, 2009). In China, where agriculture accounts for 62% of water withdrawals, groundwater pumping for irrigation accounted for only 0.6% of China's GHG emissions in 2006, a small fraction of the 17-20% share of agriculture as a whole (Wang *et al*., 2012). Where climate change reduces water resources in dry regions, desalination of seawater as an adaptation option is expected to increase GHG emissions if carbon-based fuels are used as energy source (McEvoy and Wilder, 2012).

In southeast Asia, emissions due to peatland drainage contribute 1.3-3.1% of current global CO_2 emissions from the combustion of fossil fuels (Hooijer *et al*., 2010), and peatland rewetting could substantially reduce net GHG emissions (Couwenberg *et al*., 2010). Climate change mitigation by conservation of wetlands will also benefit water quality and biodiversity (House *et al*., 2010). Irrigation can increase CO_2 storage in soils by reducing water stress and so enhancing biomass production. Irrigation in semi-arid California did not significantly increase soil organic carbon (Wu *et al*., 2008). Water management in rice paddies can reduce CH_4 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/year (16% around the year 2000), and N_2O emissions would not increase significantly (Yan *et al*., 2009).

3.8. Research and Data Gaps

Precipitation and river discharge are systematically observed, but data records are unevenly available and unevenly distributed geographically. Information on many other relevant variables, such as soil moisture, snow depth, groundwater depth and water quality, is particularly limited in developing countries. Relevant socio-economic data, such as rates of surface water and groundwater withdrawal by each sector, and information on already-implemented adaptations for stabilizing water supply, such as long-range diversions, 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 little is known about the economic aspects of climate-change impacts and adaptation options related to water resources. For example, regional damage curves need to be developed, relating the magnitudes of major water-related disasters (such as intense precipitation and surface soil dryness) to the expected costs.

There is a continuing, although narrowing, mismatch between the large scales resolved by climate models and the catchment scale at which water is managed and adaptations must be implemented. Improving the spatial resolution of regional and global climate models, and the accuracy of methods for downscaling their outputs, can produce information more relevant to water management, although the robustness of regional climate projections is still constrained by the realism of GCM simulations of large-scale drivers. More computing capacity is needed to address these problems with more ensemble simulations at high spatial resolution. More research is also needed into novel ways of combining different approaches to projection of plausible changes in relevant climate variables so as to provide robust information to water managers. 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. In addition, there is a difficulty to model and interpret results obtained from applying models at different scales and with different logics to follow the future changes on water quality. Morover, the establishment of a proper baseline to isolate the effects derived from climate change from those antropogenic caused is a major challenge.

Interactions among socio-ecological systems are not yet well considered in most impact assessments. Particularly, there are few studies on the impacts of mitigation and adaptation 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.

To support adaptation by increasing reliance on groundwater and on the coordinated and combined use of groundwater and surface water, ground-based data are needed in the form of a long-term program to monitor groundwater dynamics and stored groundwater volumes. Understanding of groundwater recharge and groundwater-surface water interactions, particularly by the assessment of experiences of conjunctive use of groundwater and surface water, needs to be better developed.

More studies are needed, especially in developing countries, on 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 climate change affect the frequency and severity of floods and droughts?

[to be placed in Section 3.4.9]

Climate change is projected to alter the frequency and magnitude of both floods and droughts. The impact is expected to vary from region to region. The few available studies suggest that flood hazards will increase over more than half of the globe, in particular in central and eastern Siberia, parts of south-east Asia including India, tropical Africa, and northern South America, but decreases are projected in parts of northern and eastern Europe, Anatolia, central and east Asia, central North America, and southern South America (*limited evidence, high agreement*).The frequency of floods in small river basins is *very likely* to increase, but that may not be true of larger watersheds because intense rain is usually confined to more limited areas. Spring snowmelt floods are *likely* to become smaller, both because less winter precipitation will fall as snow and because more snow will melt during thaws over the course of the entire winter. Worldwide, the damage from floods will increase because more people and more assets will be in harm's way.

By the end of the 21st century meteorological droughts (less rainfall) and agricultural droughts (drier soil) are projected to become longer, or more frequent, or both, in some regions and some seasons, because of reduced rainfall or increased evaporation or both. But it is still uncertain what these rainfall and soil moisture deficits might mean for prolonged reductions of streamflow and lake and groundwater levels. Droughts are projected to intensify in southern Europe and the Mediterranean region, central Europe, central and southern North America, Central America, northeast Brazil and southern Africa. In dry regions, more intense droughts will stress water-supply systems. In wetter regions, more intense seasonal droughts can be managed by current water-supply systems and by adaptation; for example, demand can be reduced by using water more efficiently, or supply can be increased by increasing the storage capacity in reservoirs.

FAQ 3.2: How will the availability of water resources be affected by climate change?

[to be placed in Section 3.5.1]

Climate models project decreases of renewable water resources in some regions and increases in others, albeit with large uncertainty in many places. Broadly, water resources are projected to decrease in many mid-latitude and dry subtropical regions, and to increase at high latitudes and in many humid mid-latitude regions (*high agreement, robust evidence)*. Even where increases are projected, there can be short-term shortages due to more variable streamflow (because of greater variability of precipitation), and seasonal reductions of water supply due to reduced snow and ice storage. Availability of clean water can also be reduced by negative impacts of climate change on water quality; for instance the quality of lakes used for water supply could be impaired by the presence of algae-producing toxins.

FAQ 3.3: How should water management be modified in the face of climate change?

[to be placed in Section 3.6.1]

Managers of water utilities and water resources have considerable experience in adapting their policies and practices to the weather. But in the face of climate change, long-term planning (over several decades) is needed for a future that is highly uncertain. A flexible portfolio of solutions that produces benefits regardless of the impacts of climate change ("low-regret" solutions) and that can be implemented adaptively, step by step, is valuable because it allows policies to evolve progressively, thus building on – rather than losing the value of – previous investments. 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. Restoring and protecting freshwater habitats, and managing natural floodplains, are additional adaptive measures that are not usually part of conventional management practice.

FAQ 3.4: Does climate change imply only bad news about water resources?

[to be placed after Section 3.6]

There is good news as well as bad about water resources, but the good news is very often ambiguous. Water may become less scarce in regions that get more precipitation, but more precipitation will probably also increase flood risk; it may also raise the groundwater table, which could lead to damage to buildings and other infrastructure or to reduced agricultural productivity due to wet soils or soil salinization. More frequent storms reduce the risk of eutrophication and algal blooms in lakes and estuaries by flushing away nutrients, but increased storm runoff will carry more of those nutrients to the sea, exacerbating eutrophication in marine ecosystems, with possible adverse impacts as discussed in Chapter 30. Water and wastewater treatment yields better results under warmer conditions, as chemical and biological reactions needed for treatment perform in general better at higher temperatures. In many rivers fed by glaciers, there will be a "meltwater dividend" during some part of the 21st century, due to increasing rates of loss of glacier ice, but the continued shrinkage of the glaciers means that after several decades the total amount of meltwater that they yield will begin to decrease (*medium confidence*). An important point is that often impacts do not become "good news" unless investments are made to exploit them. For instance, where additional water is expected to become available, the infrastructure to capture that resource would need to be developed if it is not already in place.

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 (*medium confidence*) (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 around the year 2000 (Figure RF-1; Döll and Zhang, 2010). For one climate scenario (SRES A2 emissions, HadCM3 climate model), 15% of the global land area may be negatively affected, by the 2050s, by 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, as occurs in Sweden, the annual hydrograph becomes more similar to variation in electricity demand, i.e. with a lower spring flood and increased runoff during winter months (Renofalt *et al.*, 2010).

Because biota are often adapted to a certain level of river flow variability, the projected 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 Table 3-2 in Chapter 3).

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 (Section 3.2.3 in Chapter 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).

[INSERT FIGURE RF-1 HERE

Figure RF-1: Impact of climate change relative to the impact of water withdrawals and dams on natural flows for two ecologically relevant river flow characteristics (mean annual river flow and monthly low flow Q_{90}), computed by a global water model (Döll and Zhang, 2010). Monthly Q_{90} was defined as the flow that is exceeded in 9 out 10 months. 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. Please note that the figure does not reflect spatial differences in the magnitude of change.]

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).

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°C, 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.

[INSERT FIGURE RF-2 HERE
Figure RF-2: Accumulated loss of regional species richness (gamma diversity) of macroinvertebrates as a function of glacial cover in catchment. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%, and 9-14 species are predicted to be lost with the complete disappearance of glaciers in each region, corresponding to 11, 16 and 38% of the total species richness in the three study regions in Ecuador, Europe and Alaska. Data are derived from multiple river sites from the Ecuadorian Andes and Swiss and Italian Alps, and a temporal study of a river in the Coastal Range Mountains of southeast Alaska over nearly three decades of glacial shrinkage. Each data point represents a river site or date (Alaska), and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.]

Box CC-RF References

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

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

Climate, vegetation and carbon and water cycles are intimately coupled, in particular via the simultaneous transpiration and CO_2 uptake through plant stomata in the process of photosynthesis. Hence, water flows such as runoff and evapotranspiration are affected not only directly by anthropogenic climate change as such (i.e. by changes in climate variables such as temperature and precipitation), but also indirectly by plant responses to increased atmospheric CO_2 concentrations. In addition, effects of climate change (e.g. higher temperature or altered precipitation) on vegetation structure, biomass production and plant distribution have an indirect influence on water flows. Rising CO_2 concentration affects vegetation and associated water flows in two contrasting ways, as suggested by ample evidence from Free Air CO_2 Enrichment (FACE), laboratory and modelling experiments (e.g. Leakey *et al.*, 2009; de Boer *et al.*, 2011; Reddy *et al.*, 2010). On the one hand, a *physiological* effect leads to reduced opening of stomatal apertures, which is associated with lower water flow through the stomata, i.e. lower leaf-level transpiration. On the other hand, a *structural* effect ("fertilization effect") stimulates photosynthesis and biomass production of C3 plants including all tree species, which eventually leads to higher transpiration at regional scales. A key question is to what extent the climate- and CO_2-induced changes in vegetation and transpiration translate into changes in regional and global runoff.

The physiological effect of CO_2 is associated with an increased intrinsic water use efficiency (WUE) of plants, which means that less water is transpired per unit of carbon assimilated. Records of stable carbon isotopes in woody plants (Peñuelas *et al.*, 2011) verify this finding, suggesting an increase in WUE of mature trees by 20.5% between the early 1960s and the early 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 WUE ceased to increase after 1970 (Gagen *et al.*, 2011). Analysis of long-term whole-ecosystem carbon and water flux measurements from 21 sites in North American temperate and boreal forests corroborates a notable increase in WUE over the two past decades (Keenan *et al.*, 2013). An increase in global WUE over the past century is supported by ecosystem model results (Ito and Inatomi, 2012).

A key influence on the significance of increased WUE for large-scale transpiration is whether vegetation structure and production has remained approximately constant (as assumed in the global modelling study by Gedney *et al.*, 2006) or has increased in some regions due to the structural CO_2 effect (as assumed in models by Piao *et al.*, 2007;

Gerten *et al*., 2008). While field-based results vary considerably among sites, tree ring studies suggest that tree growth did not increase globally since the 1970s in response to climate and CO_2 change (Peñuelas *et al.*, 2011; Andreu-Hayles *et al.*, 2011). However, basal area measurements at over 150 plots across the tropics suggest that biomass and growth rates in intact tropical forests have increased in recent decades (Lewis *et al*., 2009). This is also confirmed for 55 temperate forest plots, with a suspected contribution of CO_2 effects (McMahon *et al.*, 2010). Satellite observations analysed in Donohue *et al.* (2013) suggest that an increase in vegetation cover by 11% in warm drylands (1982–2010 period) is attributable to CO_2 fertilization. Owing to the interplay of physiological and structural effects, the net impact of CO_2 increase on global-scale transpiration and runoff remains rather poorly constrained. This is also true because nutrient limitation, often omitted in modelling studies, can suppress the CO_2 fertilization effect (see Rosenthal and Tomeo, 2013).

Therefore, 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 the physiological CO_2 effect (lower transpiration) contributed to a supposed increase in global runoff seen in reconstructions by Labat *et al.* (2004). However, a more recent analysis based on a more complete dataset (Dai *et al*., 2009) suggested that river basins with decreasing runoff outnumber basins with increasing runoff, such that a small decline in global runoff is *likely* for the period 1948–2004. Hence, detection of vegetation contributions to changes in water flows critically depends on the availability and quality of hydrometeorological observations (Haddeland *et al.*, 2011; Lorenz and Kunstmann, 2012). Overall, the evidence since AR4 suggests that climatic variations and trends have been the main driver of global runoff change in the past decades; both CO_2 increase and land use change have contributed less (Piao *et al*., 2007; Gerten *et al*., 2008; Alkama *et al.*, 2011; Sterling *et al.*, 2013). Oliveira *et al.* (2011) furthermore pointed to the importance of changes in incident solar radiation and the mediating role of vegetation; according to their global simulations, a higher diffuse radiation fraction during 1960–1990 may have increased evapotranspiration in the tropics by 3% due to higher photosynthesis from shaded leaves.

It is uncertain how vegetation responses to future increases in CO_2 and to climate change will modulate the impacts of climate change on freshwater flows. 21st century continental- and basin-scale runoff is projected by some models to either increase more or decrease less when the physiological CO_2 effect is included in addition to climate change effects (Betts *et al.*, 2007; Murray *et al.,* 2012). This could somewhat ease the increase in water scarcity anticipated in response to future climate change and population growth (Gerten *et al.*, 2011; Wiltshire *et al.*, in press). In absolute terms, the isolated effect of CO_2 has been modelled to increase future global runoff by 4–5% (Gerten *et al.*, 2008) up to 13% (Nugent and Matthews, 2012) compared to the present, depending on the assumed CO_2 trajectory and whether feedbacks of changes in vegetation structure and distribution to the atmosphere are accounted for (they were not in Nugent and Matthews, 2012). In a global model intercomparison study (Davie *et al.*, in press), two out of four models projected stronger increases and, respectively, weaker decreases in runoff when considering CO_2 effects compared to simulations with constant CO_2 concentration (consistent with above findings, though magnitudes differed between the models), but two other models showed the reverse. Thus, the choice of models and the way they represent the coupling between CO_2, stomatal closure and plant growth is a source of uncertainty, as also suggested by Cao *et al.* (2009). Lower transpiration due to rising CO_2 concentration may also affect future regional climate change itself (Boucher *et al.*, 2009) and enhance the contrast between land and ocean surface warming (Joshi *et al.*, 2008). Overall, although physiological and structural effects will influence water flows in many regions, precipitation and temperature effects are *likely* to remain the prime influence on global runoff (Alkama *et al.*, 2010).

An application of a soil-vegetation-atmosphere-transfer model indicates complex responses of groundwater recharge to vegetation-mediated changes in climate, with computed groundwater recharge being always larger than would be expected from just accounting for changes in rainfall (McCallum *et al.*, 2010). Another study found that even if precipitation slightly decreased, groundwater recharge might increase as a net effect of vegetation responses to climate change and CO_2 rise, i.e. increasing WUE and either increasing or decreasing leaf area (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 site 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).

Using a large ensemble of climate change projections, Konzmann *et al.* (2013) put hydrological changes into an agricultural perspective and suggested that the net result of physiological and structural CO_2 effects on crop irrigation requirements would be a global reduction (Figure VW-1). Thus, adverse climate change impacts on irrigation requirements and crop yields might be partly buffered as WUE and crop production improve (Fader *et al.*, 2010). However, substantial CO_2-driven improvements will only be realized if proper management abates limitation of plant growth by nutrient availability or other factors.

[INSERT FIGURE VW-1 HERE
Figure VW-1: Percentage change in net irrigation requirements of 11 major crops from 1971–2000 to 2070–2099 on areas currently equipped for irrigation, assuming current management practices. Top: impact of climate change including physiological and structural crop responses to increased atmospheric CO_2 concentration (maximum effect in the absence of co-limitation by nutrients). Bottom: impact of climate change only. Shown is the median change derived from climate change projections by 19 GCMs (based on the SRES A2 emissions scenario) used to force a vegetation and hydrology model. Modified after Konzmann *et al.* (2013).]

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 atmosphere such as in the Amazon region (Port *et al.*, 2012; Saatchi *et al.*, 2013). One model in the study by Davie *et al.* (in press) showed regionally diverse climate change effects on vegetation distribution and structure, which had a much weaker effect on global runoff than the structural and physiological CO_2 effects. As water, carbon and vegetation dynamics evolve synchronously and interactively under climate change (Heyder *et al.*, 2011; Gerten *et al.*, in press), it remains a challenge to disentangle the individual effects of climate, CO_2 and land cover change on the water cycle.

Box CC-VW References

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Box CC-WE: The Water-Energy-Food/Feed/Fiber Nexus as Linked to Climate Change

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Water, energy, and food/feed/fiber are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure WE-1. The depth and intensity of those linkages vary enormously between countries, regions and production systems. Energy technologies (e.g. biofuels, hydropower, thermal power plants), transportation fuels and modes, and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops and forages) may require significant amounts of water (Sections 3.7.2, 7.3.2, 10.2, 10.3.4, 22.3.3, 25.7.2; Allan, 2003; King and Weber 2008; McMahon and Price, 2011; Macknick *et al*., 2012a). In irrigated agriculture, climate, irrigating procedure, crop choice and yields determine water requirements per unit of produced crop. In areas where water (and wastewater) must be pumped and/or treated, energy must be provided (Asano et al., 2006; Khan and Hanjra, 2009; USEPA, 2010; Gerten et al., 2011). While food production, refrigeration, transport and processing 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 (Section 7.3.2, Box 25-10; Diffenbaugh et al., 2012; Skaggs et al., 2012) *(robust evidence, high agreement)*. Food and crop wastes, and wastewater, may be used as sources of energy, saving not only the consumption of conventional non-renewable fuels used in their traditional processes, but also the consumption of the water and energy employed for processing or treatment and disposal (Schievano et al., 2009; Sung et al., 2010; Olson, 2012). Examples of this can be found in several countries across all income ranges. For example, sugar cane by-products are increasingly used to produce electricity or for cogeneration (McKendry, 2002; Kim and Dale 2004) for economic benefits, and increasingly as an option for greenhouse gas mitigation.

[INSERT FIGURE WE-1 HERE
Figure WE-1: The water-energy-food nexus as related to climate change. The interlinkages of supply/demand, quality and quantity of water, energy and food/feed/fiber with changing climatic conditions have implications for both adaptation and mitigation strategies.]

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) (Sections 10.2.2 10.3.4, 25.7.4; van Vliet et al., 2012; Davies et al., 2013) *(robust evidence, high agreement).* Water for biofuels, for example, under the IEA Alternative Policy Scenario, which has biofuels production increasing to 71 EJ in 2030, has been reported by Gerbens-Leenes et al. (2012) to drive global consumptive irrigation water use 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 is also required for mining (Section 25.7.3), processing, and residue disposal of fossil and nuclear fuels or their byproducts. Water for energy currently ranges from a few percent in most developing countries to more than 50% of freshwater withdrawals in some developed countries, depending on the country (Kenny et al., 2009; WEC, 2010). Future water requirements will depend on electricity demand growth, the portfolio of generation technologies and water management options employed (WEC, 2010; Sattler et al., 2012) *(medium evidence, high agreement)*. Future water availability for energy production will change due to climate change (Sections 3.4, 3.5.1, 3.5.2.2) *(robust evidence, high agreement).*

Water may require significant amounts of energy for lifting, transport and distribution and for its treatment either to use it or to depollute it. Wastewater and even excess rainfall in cities requires energy to be treated or disposed. Some 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 potable water from ground/surface water sources vs. desalinated seawater (Box 25-2, Tables 25-6 and 25-7; Macknick et al., 2012b; Plappally and Lienhard, 2012). 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 India, for example, 19% of total electricity use in 2012 was for agricultural purposes (Central Statistics Office, 2013), with a large share for groundwater pumping. Pumping from greater depth increases energy demand significantly– electricity use (kWhr/m^3 of water) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard, 2012). The reuse of appropriate wastewater for irrigation (reclaiming both water and energy-intense nutrients) may increase agricultural yields, save energy, and prevent soil erosion (Smit and Nasr, 1992; Jimenez, 1996; Wichelns et al., 2007; Raschid-Sally and Jayakody, 2008) *(medium confidence)*. More energy efficient treatment methods enable poor quality (“black”) wastewater to be treated to quality levels suitable for discharge into water courses, avoiding additional fresh water and associated energy demands (Keraita et al, 2008). If properly treated to retain nutrients, such treated water may increase soil productivity, contributing to increased crop yields/food security in regions unable to afford high power bills or expensive fertilizer (Oron, 1996; Lazarova and Bahri, 2005; Redwood and Huibers, 2008; Jimenez, 2009) *(high confidence)*.

Linkages among water, energy, food/feed/fiber and climate are also strongly related to land use and management (Section 4.4.4, Box 25-10) *(robust evidence, high agreement)*. Land degradation often reduces efficiency of water and energy use (e.g. resulting in higher fertilizer demand and surface runoff), and compromises food security (Sections 3.7.2, 4.4.4). On the other hand, afforestation activities to sequester carbon have important co-benefits of reducing soil erosion and providing additional (even if only temporary) habitat (see Box 25-10) but may reduce renewable water resources. Water abstraction for energy, food or biofuel production or carbon sequestration can also compete with minimal environmental flows needed to maintain riverine habitats and wetlands, implying a potential conflict between economic and other valuations and uses of water (Sections 25.4.3 and 25.6.2, Box 25-10) *(medium evidence, high agreement)*. Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water and climate (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 and water 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 report.

The interconnectivity of food/fiber, water, land use, energy and climate change, including the perhaps not yet well understood cross-sector impacts, are increasingly important in assessing the implications for adaptation/mitigation policy decisions. Fuel-food-land use-water-GHG mitigation strategy interactions, particularly related to bioresources for food/feed, power, or fuel, suggest that combined assessment of water, land type and use requirements, energy requirements and potential uses and GHG impacts often epitomize the interlinkages. For example, mitigation scenarios described in the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC, 2011) indicate up to 300EJ of biomass primary energy by 2050 under increasingly stringent mitigation scenarios. Such high levels of biomass production, in the absence of technology and process/management/operations change, would have significant implications for land use, water and energy, as well as food production and pricing. Consideration of the interlinkages of energy, food/feed/fiber, water, land use and climate change is increasingly recognized as critical to effective climate resilient pathway decision making *(medium evidence, high agreement),* although tools to support local- and regional-scale assessments and decision-support remain very limited.

Box CC-WE References

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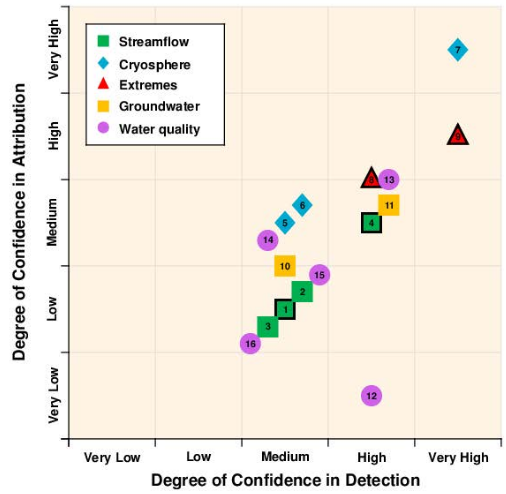
Table 3-1: Selected examples, mainly from Section 3.2, of the observation, detection and attribution of impacts of climate change on freshwater resources. Observed hydrological changes are attributed here to their climatic drivers, not all of which are necessarily anthropogenic; in the diagram, symbols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

1: Gerten *et al*. (2008), Piao *et al.* (2007), Alkama *et al.* (2011); 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, 1960-1994)	Mainly climatic change, and to a lesser degree CO_2 increase and land-use change	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-1990s)	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, 1980s to 2000s	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, and possibly increased temperature; multiple confounding factors	10
Decreased groundwater recharge (Kashmir, 1985-2005)	Decreased winter precipitation	11
Increased dissolved organic carbon in upland lakes (UK, 1988-2004)	Increased temperature and precipitation; multiple confounding factors	12
Increased anoxia in a reservoir, moderated during ENSO (El Niño-Southern Oscillation) 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: Effects of different GHG emissions scenarios on hydrological changes and freshwater-related impacts of climate change on humans and ecosystems. Among the SRES scenarios, GHG emissions are highest in A1f and A2, lower in A1 and B2, and lowest in B1. RCP8.5 is similar to A2, while the lower emissions scenarios RCP6.0 and RCP4.5 are similar to B1. RCP2.6 is a very low emissions scenario (Figure 1-4 and Section 1.1.3.1 in Chapter 1). The studies in the table give global warming (GW: global mean temperature rise, quantified as the CMIP5 model mean) over different reference periods, typically since pre-industrial. GW is projected to be, for RCP8.5, approximately 2°C in the 2040s and 4°C in the 2080s. For RCP6.0, GW is 2°C in the 2060s and 2.5°C in the 2080s, while in RCP2.6, GW stays below 1.8°C throughout the 21st century (Figure 1-4 in Chapter 1). Population scenario SSP2 assumes a medium population increase.

Type of hydrological change or impact	Description of indicator	Hydrological change or impact in different emissions scenarios or for different degrees of global warming (GW)	Reference
Decrease of renewable water resources, global scale	Percent of global population affected by a water resource decrease of more than 20% as compared to the 1990s (mean of 5 GCMs and 11 global hydrological models, population scenario SSP2)	Up to 2°C above the 1990s (GW 2.7°C) each degree of GW affects an additional 7%	Schewe *et al*. (2013)
Decrease of renewable groundwater resources, global scale	Percent of global population affected by a groundwater resource decrease of more than 10% by the 2080s as compared to the 1980s (mean and range of 5 GCMs, population scenario SSP2)	RCP2.6: 24% (11-39%) RCP4.5: 26% (23-32%) RCP6.0: 32% (18-45%) RCP8.5: 38% (27-50%)	Portmann *et al.* (2013)
Exposure to floods, global scale	Percent of global population annually exposed, in the 2080s, to a flood corresponding to the 100-year flood discharge for the 1980s (mean and range of 5-11 GCMs, population constant at 2005 values)	RCP2.6: 0.4% (0.2-0.5%) RCP4.5: 0.6% (0.4-1.0%) RCP6.0: 0.7% (0.3-1.1%) RCP8.5: 1.2% (0.6-1.7%) GW 2°C: 0.5% (0.3-0.6%) GW 4°C: 1.2% (0.8-2.2%) 1980s: 0.1% (0.04-0.16%)	Hirabayashi *et al.* (2013)
Change in irrigation water demand, global scale	Change of required irrigation water withdrawals by the 2080s (on area irrigated around 2000) as compared to the 1980s (range of 3 GCMs)	RCP2.6: -0.2-1.6% RCP4.5: 1.9-2.8% RCP8.5: 6.7-10.0%	Hanasaki *et al.* (2013)
River flow regime shifts from perennial to intermittent and vice versa, global scale	Percent of global land area (except Greenland and Antarctica) affected by regime shifts between the 1970s and the 2050s (range of 2 GCMs)	SRES B2: 5.4-6.7% SRES A2: 6.3-7.0%	Döll and Müller Schmied (2012)
Water scarcity	Percent of global population living in countries with less than 1300 m^3/year of per-capita in the 2080s (mean of 17 GCMs, population constant at 2000 values)	No significant differences between SRES B1 and A2	Gerten *et al.* (2011)
New or aggravated water scarcity	Percent of global population living in river basins with new or aggravated water scarcity around 2100 as compared to 2000 (less than 1000 m^3/year of per-capita blue water resources) (median of 19 GCMs, population constant at 2000 values)	GW 2°C: 8% GW 3.5°C: 11% GW 5°C: 13%	Gerten *et al.* (2013)
Exposure to water scarcity	Population in water-stressed watersheds (less than 1000 m^3/year of	For emissions scenarios with 2ºC target, compared to SRES	Arnell *et al*. (2013)

	per-capita blue water resources) exposed to an increase in stress (1 GCM)	A1: 5-8% impact reduction in 2050 10-20% reduction in 2100	
Change of groundwater recharge in the whole of Australia	Probability that groundwater recharge decreases to less than 50% of the 1990s value by 2050 (16 GCMs)	GW 1.4°C: close to 0 almost everywhere GW 2.8°C: in western Australia 0.2-0.6, in central Australia 0.2-0.3, elsewhere close to 1	Crosbie *et al*. (2013a)
Change in groundwater recharge in East Anglia, UK	Percent change between baseline and future groundwater recharge, in %, by the 2050s (1 GCM)	SRES B1: -22% SRES A1f: -26%	Holman *et al*. (2009)
Change of river discharge, groundwater recharge and hydraulic head in groundwater in two regions of Denmark	Changes between the 1970s and the 2080s (1 regional climate model)	Differences between SRES B2 and A2 are very small compared to the changes between the 1970s and the 2080s in each scenario	van Roosmalen *et al.* (2007)
River flow regime shift for river in Uganda	Shift from bimodal to unimodal (1 GCM)	Occurs in scenarios with GW of at least 4.3°C but not for smaller GW	Kingston and Taylor (2010)
Agricultural (soil moisture) droughts in France	Mean duration, affected area and magnitude of short and long drought events throughout the 21st century (1 GCM)	Smaller increases over time for SRES B1 than for A2 and A1B	Vidal *et al.* (2012)
Salinization of artificial coastal freshwater lake IJsselmeer in the Netherlands (a drinking water source) due to seawater intrusion	(1) Daily probability of exceedance of maximum allowable concentration (MAC) of chloride (150 mg/liter), (2) Maximum duration of MAC exceedance (2050, 1 GCM)	Reference period 1997-2007 (GW 0.8°C): (1) 2.5%, (2) 103 days GW 1.8°C, no change in atmospheric circulation: (1) 3.1%, (2) 124 days GW 2.8°C and change in atmospheric circulation: (1) 14.3%, (2) 178 days	Bonte and Zwolsman (2010)
Decrease of hydropower production at Lake Nasser, Egypt	Reduction of mean annual hydropower production by the 2080s compared to hydropower production 1950-99 (11 GCMs)	SRES B1: 8% SRES A2: 7%	Beyene *et al*. (2010)
Reduction of usable capacity of thermal power plants in Europe and USA due to low river flow and excessive water temperature	Number of days per year with a capacity reduction of more than 50% (for existing power plants) (2031-2060, 3 GCMs)	Without climate change: 16 SRES B1: 22 SRES A2: 24	van Vliet *et al*. (2012)
Flood damages in Europe (EU27)	(1) Expected annual damages, in 2006- €, (2) Expected annual population exposed (2080s, 2 GCMs)	SRES B2: (1) 14-15 billion €/year, (2) 440,000-470,000 people SRES A2: (1) 18-21 billion €/year, (2) 510,000-590,000 people Reference period: (1) 6.4 billion €/year, (2) 200,000 people	Feyen *et al*. (2012)

Table 3-3: Categories of climate change adaptation options for the management of freshwater resources.

OPTION	A+M
Institutional	
Support integrated water resources management, including the integrated management of land considering specifically negative and positive impacts of climate change	X
Promote synergy of water and energy savings and efficient use	X
Identify “low-regret policies” and build a portfolio of relevant solutions for adaptation	X
Increase resilience by forming water utility network working teams	
Build adaptive capacity	
Improve and share information	X
Adapt the legal framework to make it instrumental for addressing climate change impacts	X
Develop financial tools (credit, subsidies and public investment) for the sustainable management of water, and for considering poverty eradication and equity	
Design and operation	
Design and apply decision-making tools that consider uncertainty and fulfill multiple objectives	
Revise design criteria of water infrastructure to optimize flexibility, redundancy and robustness	
Ensure plans and services are robust, adaptable or modular, give good value, are maintainable, and have long-term benefits, especially in low-income countries	X
Operate water infrastructure so as to increase resilience to climate change for all users and sectors	
When and where water resources increase, alter dam operations to allow freshwater ecosystems to benefit	
Take advantage of hard and soft adaptation measures	X
Carry out programs to protect water resources in quantity and quality	
Increase resilience to climate change by diversifying water sources(1) and improving reservoir management	X
Reduce demand by controlling leaks, implementing water-saving programs, cascading and reusing water	X
Improve design and operation of sewers, sanitation and wastewater treatment infrastructure to cope with variations in influent quantity and quality	
Provide universal sanitation with technology locally adapted, and provide for proper disposal and reintegration of used water into the environment or for its reuse	
Reduce impact of natural disasters	
Implement monitoring and early warning systems	
Develop contingency plans	
Improve defenses and site selection for key infrastructure that is at risk of floods	
Design cities and rural settlements to be resilient to floods	
Seek and secure water from a diversity (spatially and source-type) of sources to reduce impacts of droughts and variability in water availability	
Promote both the reduction of water demand and the efficient use of water by all users	
Improve irrigation efficiency and reduce demand for irrigation water	X
Promote switching to more appropriate crops (drought-resistant, salt-resistant; low water demand)	X
Plant flood- or drought-resistant crop varieties	
Agricultural irrigation	
Reuse wastewater to irrigate crops and use soil for carbon sequestration	X
Industrial use	
When selecting alternative sources of energy, assess the need for water	X
Relocate water-thirsty industries and crops to water-rich areas	
Implement industrial water efficiency certifications	X

A+M: may assist both adaptation and mitigation
(1) This includes water reuse, rain water harvesting, and desalination, among others.

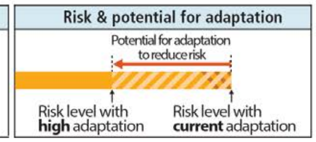
With information from: Arkell (2011a; 2011b); Andrews (2009); Bahri (2009); Bowes *et al*. (2012); de Graaf and der Brugge (2010); Dembo (2010); Dillon and Jiménez (2008); Elliott *et al*. (2011); Emelko *et al*. (2011); Godfrey *et al*. (2010); Howard *et al*. (2010); Jiménez and Asano (2008); Jiménez (2011); Keller (2008); Kingsford (2011); Mackay and Last (2010); Major *et al*. (2011); Marsalek *et al*. (2006); McCafferty (2008); McGuckin (2008); Mogaka *et al*. (2006); Mukhopadhyay and Dutta (2010); Munasinghe (2009); 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); Wang X. *et al*. (2011); Whitehead *et al*. (2009b); Zwolsman *et al*. (2010)

Table 3-4: Key risks from climate change and the potential for reducing risk through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments by chapter authors, with evaluation of evidence and agreement in supporting chapter sections. Each key risk is characterized as very low to very high. Risk levels are presented in three time frames: the present, near-term (here assessed over 2030-2040), and longer term (here assessed over 2080-2100). Sources: Xie et al., 2006; Döll, 2009; Kaser et al., 2010; Arnell et al., 2011; Huss, 2011; Jóhannesson et al., 2012; Seneviratne et al., 2012; Arnell and Gosling, 2013; Dankers et al., 2013; Gosling and Arnell, 2013; Hanasaki et al., 2013; Hirabayashi et al., 2013; Kundzewicz et al., 2013; Portmann et al., 2013; Radić et al., 2013; Schewe et al., 2013; WGI AR5 Chapter 13.

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation (Very low – Medium – Very high)
Flood risks associated with climate change increase with increasing greenhouse gas emissions (*high agreement, medium confidence*)	By 2100, the number of people exposed annually to a 20th-century 100-year flood is projected to be three times greater for very high emissions (RCP8.5) than for very low emissions (RCP2.6).		3.4.8	Present Near-term (2030-2040) Long-term (2080-2100) 2°C Long-term (2080-2100) 4°C	
Climate change is projected to reduce renewable water resources significantly in most dry subtropical regions (*high agreement, robust confidence*)	This will exacerbate competition for water among agriculture, ecosystems, settlements, industry and energy production, affecting regional water, energy and food security.		3.5.1	Present Near-term (2030-2040) Long-term (2080-2100) 2°C Long-term (2080-2100) 4°C	
Because nearly all glaciers are too large for equilibrium with the present climate, there is a committed water-resources change during much of the 21st century, and changes beyond the committed change are expected due to continued warming; in glacier-fed rivers, total meltwater yields from stored glacier ice will increase in many regions during the next decades but decrease thereafter (*high agreement, robust confidence*)	Continued loss of glacier ice implies a shift of peak discharge from summer to spring, except in monsoonal catchments, and possibly a reduction of summer flows in the downstream parts of glacierized catchments.		3.4.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C Long-term (2080-2100) 4°C	

Climatic drivers of impacts		
Warming trend	Drying trend	Extreme precipitation

Risk & potential for adaptation



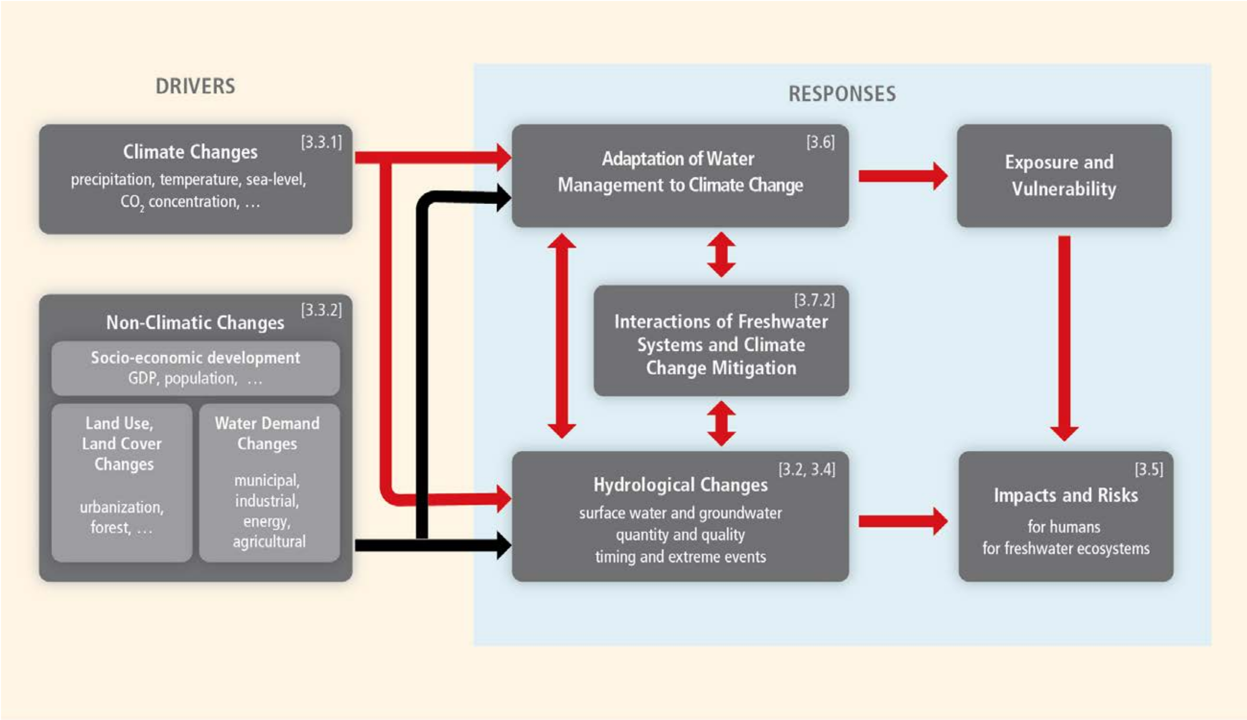
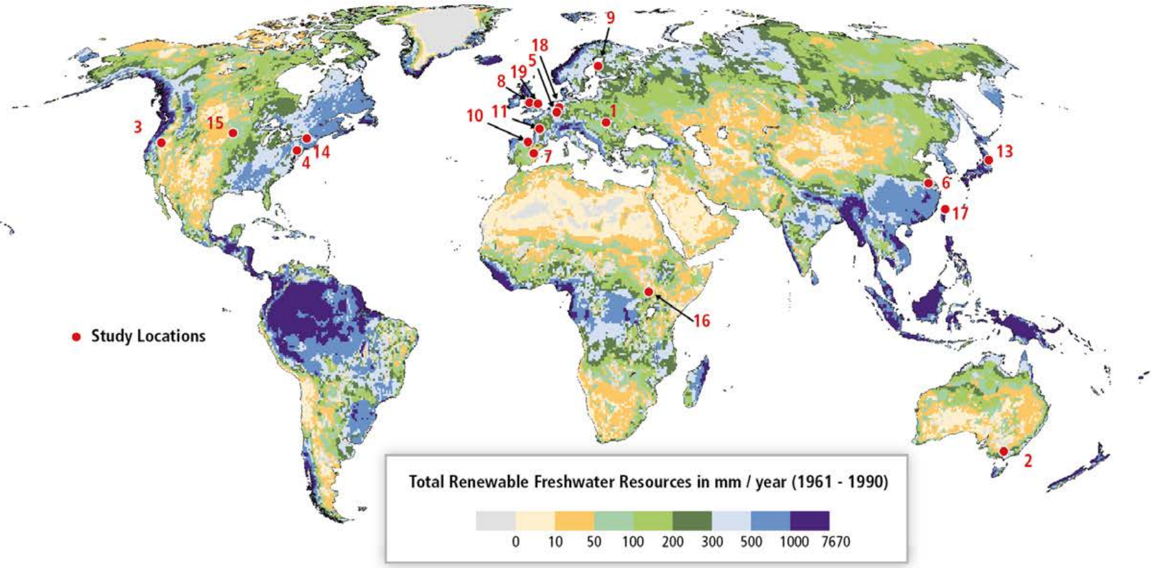


Figure 3-1: Framework (boxes) and linkages (arrows) for considering impacts of climatic and social changes on freshwater systems, and consequent impacts on and risks for humans and freshwater ecosystems. Both climatic (Section 3.3.1) and non-climatic (Section 3.3.2) drivers have changed natural freshwater systems (Section 3.2) and are expected to continue to do so (Section 3.4). They also stimulate adaptive measures (Section 3.6). Hydrological and water-management changes interact with each other and with measures to mitigate climate change (Section 3.7.2). Adaptive measures influence the exposure and vulnerability of human beings and ecosystems to water-related risks (Section 3.5).



#	Location	Study Period	Observation on water quality	Reference
1	Danube River, Bratislava, Slovakia	1926-2005	The water temperature is rising but the trend of the weighted long term average temperature values resulted close to zero because of the inter-annual distribution of the mean monthly discharge.	Pekarova et al., 2008
2	Purrumbete, Colac & Bullen Merri Lakes, Victoria, Australia	1984-2000	The increases in salinity and nutrient content were associated with the air temperature increase; salinity in addition was associated with variations in the effective precipitation.	Tibby and Tiller, 2007
3	Lake Tahoe, California and Nevada States, US	1970-2007	Thermal stability resulting from a higher ambient temperature decreased the dissolved oxygen content.	Sahoo et al., 2010
4	Neuse River Estuary, North Carolina, US	1979-2003	Intense storms and hurricanes flushed nutrients from the estuary reducing eutrophic conditions and the risk of algal blooms.	Paerl et al., 2006; Paerl and Huisman, 2008
5	River Meuse, western Europe	1976-2003	Increase of water temperature and the content of major elements and some heavy metals were associated with droughts. Algal blooms resulted from a higher nutrient content due to higher water temperature and longer residence time.	van Vliet and Zwolsman, 2008
6	Lake Taihu, Wuxi, Jiangsu, China	2007	The lake already suffering from periodic cyanobacterial blooms, was affected by a very intensive bloom in May 2007 attributed to an unusually warm spring and leading to the presence of Microcystis toxins in the water. This forced two million people to drink bottled water for at least one week.	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.	Marcé et al., 2010
8	22 upland waters in UK	1988-2002	Dissolved organic matter increased due to temperature increase but also to rainfall variations, acid deposition, land-use, and CO_2 enrichment.	Evans et al., 2005
9	Coastal rivers from western Finland	1913-2007	Low pH values associated with higher rainfall and river discharge in an acid sulphate soil basin.	Saarinen et al., 2010
		1961-2007	Critical values of dissolved organic carbon associated with higher rainfall and river discharge.	
10	15 pristine mountain rivers, Northern Spain	1973-2005	For a semiarid area, a clear relationship between increases in air temperature and a higher nutrient and dissolved organic carbon content.	Benítez-Gilabert et al., 2010
11	30 coastal rivers and groundwater of Western France	1973-2007 (2-6 years)	Inter-annual variations in the nutrient content associated with air temperature, rainfall and management practices changes. These effects were not observed in groundwater because of the delay in response time and the depuration of soil on water.	Gascuel-Odoux et al., 2010
12	Girnock, Scotland	14 months	Higher risks of faecal pollution clearly related to rainfall during the wet period	Tetzlaff et al., 2010
13	27 rivers in Japan	1987-1995	Increases in organic matter and sediment and decreases in the dissolved oxygen content associated with increases in ambient temperature. Precipitation increases and variations associated with increase in the organic matter, sediments and chemical oxygen demand content in water.	Ozaki et al., 2003
14	Conestoga River Basin, Pennsylvania, US	1977-1997	Close association between annual loads of total nitrogen and annual precipitation increases.	Chang 2004
15	US	1948-1994	Increased rainfall and runoff associated with site-specific outbreaks of waterborne disease.	Curriero et al., 2001
16	Northern and Eastern Uganda	1999-2001, 2004, 2007	Elevated concentrations of faecal coliforms observed in groundwater-fed water supplies during the rainy season.	Tumwine et al. 2002, 2003; Taylor et al., 2009
17	Taiwan, China	1998	The probability of detecting cases of enterovirus infection was greater than 50% with rainfall rates >31 mm/h. The higher the rainfall rate, the higher the probability of an enterovirus epidemic.	Jean et al., 2006
18	Rhine Basin	1980-2001	Nutrient content in rivers followed seasonal variations in precipitation which were also linked to erosion within the basin.	Loos et al., 2009
19	River Thames, England	1868-2008	Higher nutrient contents were associated to changes in river runoff and land use.	Howden et al., 2010

Figure 3-2: Observations of the impacts of climate on water quality.

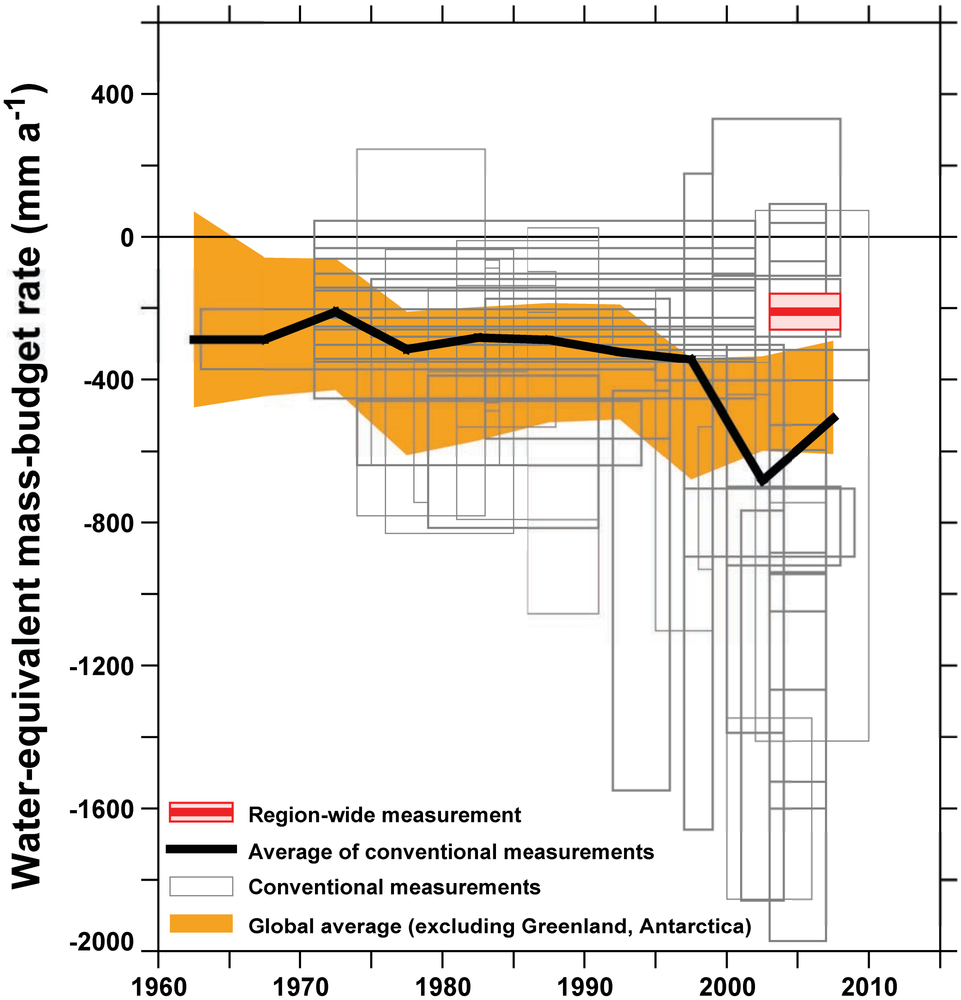


Figure 3-3: All published glacier mass balance measurements from the Himalaya (based on Bolch *et al*., 2012). To emphasize the variability of the raw information, each measurement is shown as a box of height ±1 standard deviation centred on the average balance (±1 standard error for multi-annual measurements).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

[Illustration to be redrawn to conform to IPCC publication specifications.]

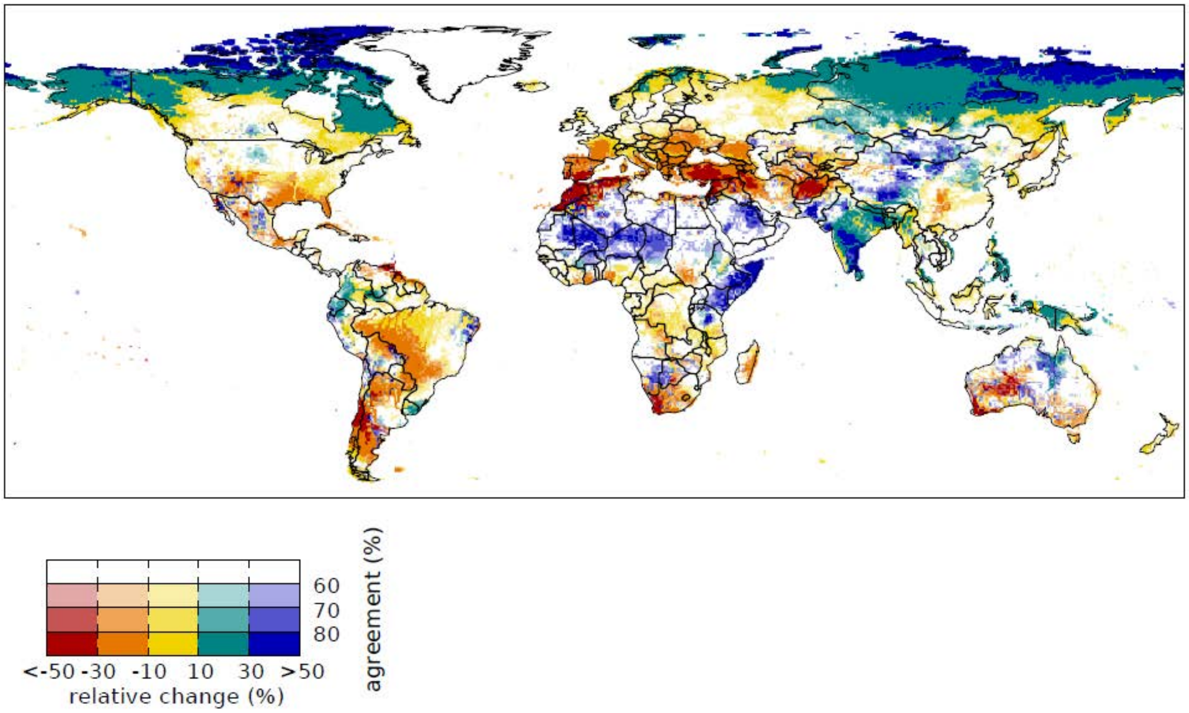


Figure 3-4: Percentage change of mean annual streamflow for a global mean temperature rise of 2°C above 1980–2010 (2.7°C above pre-industrial). Color hues show the multi-model mean change across 4 GCMs and 11 global hydrological models (GHMs), and saturation shows the agreement on the sign of change across all 55 GHM-GCM combinations (percentage of model runs agreeing on the sign of change) (Schewe *et al*., 2013).
[Illustration to be redrawn to conform to IPCC publication specifications.]

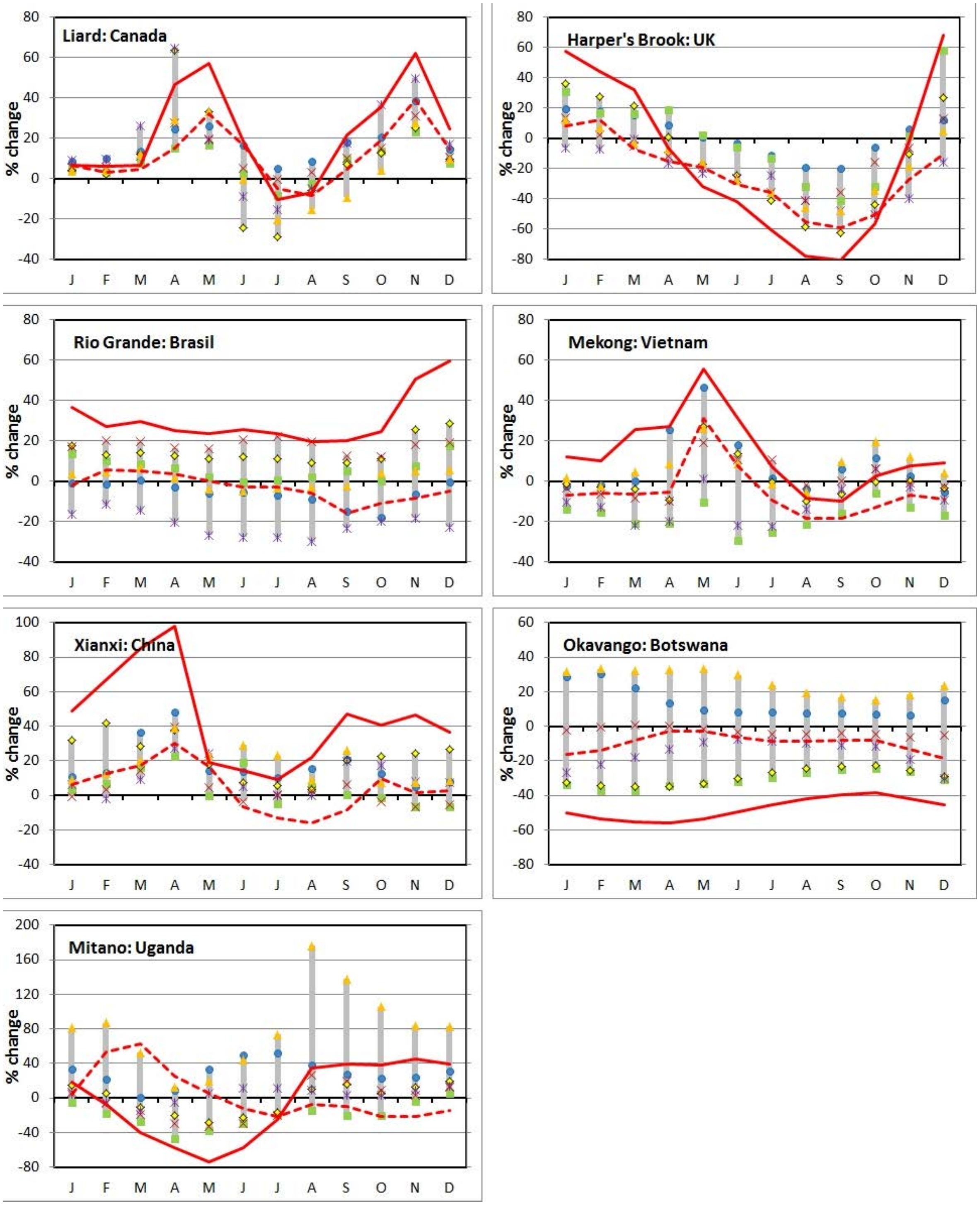
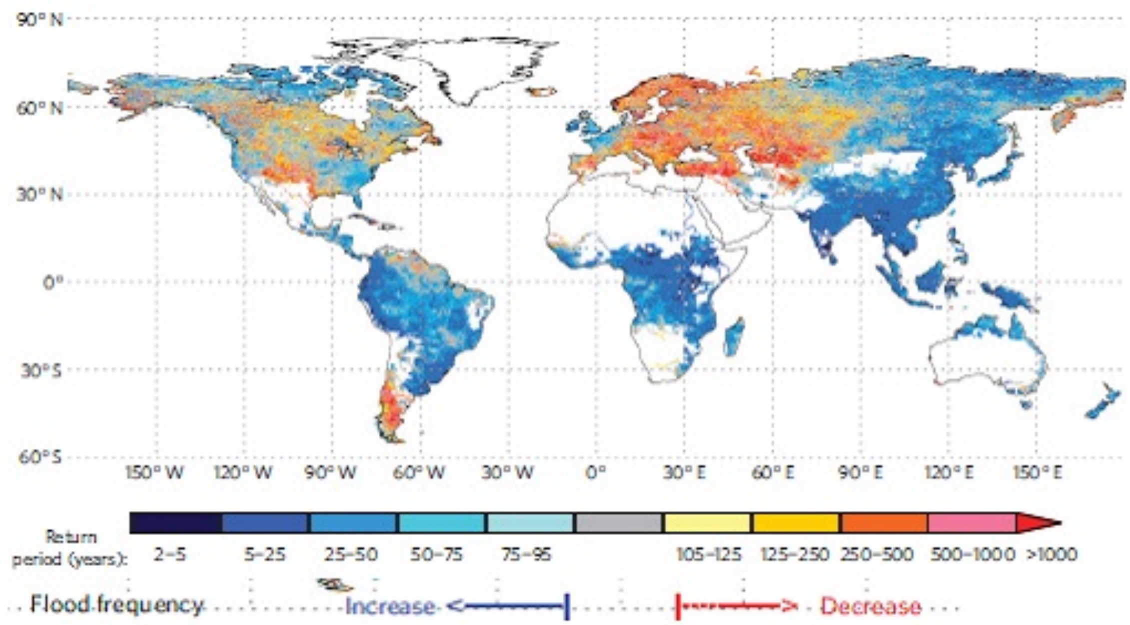


Figure 3-5: Change in mean monthly runoff across seven climate models in seven catchments, with a 2ºC increase in global mean temperature above 1961-1990 (Arnell, 2011; Hughes *et al.*, 2011; Kingston and Taylor, 2010; Kingston *et al.*, 2011; Nobrega *et al.*, 2011; Thorne, 2011; Xu *et al.*, 2011). One of the seven climate models (HadCM3) is highlighted separately, showing changes with both a 2ºC increase (dotted line) and a 4ºC increase (solid line). **[Illustration to be redrawn to conform to IPCC publication specifications.]**

a)



b)

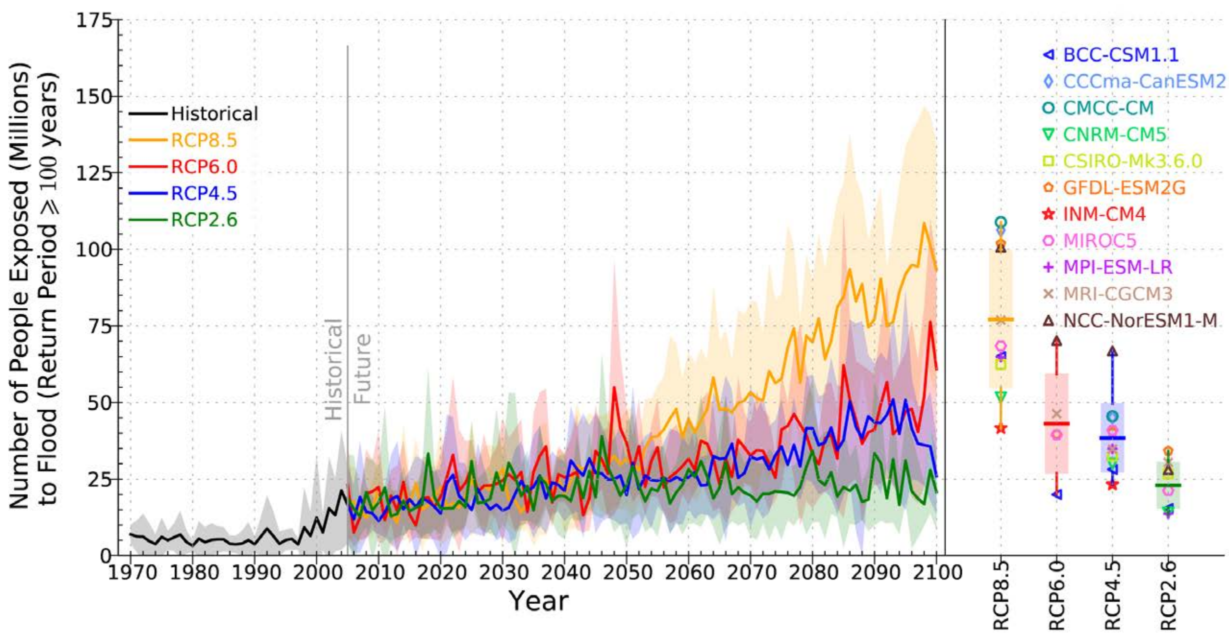


Figure 3-6: a) Multi-model median return period (years) in the 2080s for the 20th-century 100-year flood (Hirabayashi *et al*., 2013), based on one hydrological model driven by 11 CMIP5 GCMs under RCP8.5. At each location the magnitude of the 100-year flood was estimated by fitting a Gumbel distribution function to time series of simulated annual maximum daily discharge in 1971–2000, and the return period of that flood in 2071–2100 was estimated by fitting the same distribution to discharges simulated for that period. b) Global exposure to the 20th-century 100-year flood (or greater) in millions of people (Hirabayashi *et al*., 2013). Left: ensemble means of historical (black thick line) and future simulations (colored thick lines) for each scenario. Shading denotes ±1 standard deviation. Right: maximum and minimum (whiskers), mean (horizontal thick lines within each bar), ±1 standard deviation (box) and projections of each GCM (colored symbols) averaged over the 21st century. The

impact of 21st-century climate change is emphasized by fixing the population to that of 2005. Annual global flood exposure increases over the century by 4-14 times as compared to the 20th century [4±3 (RCP2.6), 7±5 (RCP4.5), 7±6 (RCP6.0) and 14±10 (RCP8.5) times, or 0.1% to 0.4-1.2% of the global population in 2005)]. Under a scenario of moderate population growth (UN, 2011), the global number of exposed people is projected to increase by a factor of 7-25, depending on the RCP, with strong increases in Asia and Africa due to high population growth.
[Illustration to be redrawn to conform to IPCC publication specifications.]

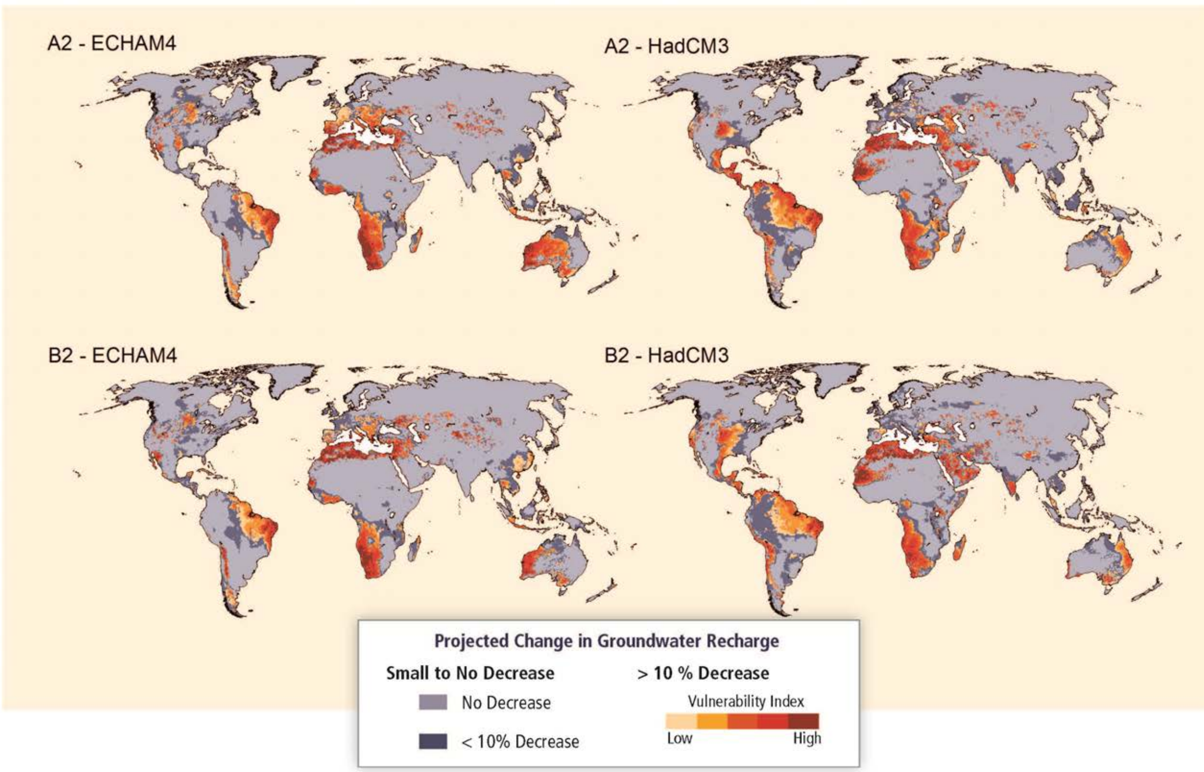


Figure 3-7: Human vulnerability to climate-change induced decreases of renewable groundwater resources by the 2050s. Lower (B2) and higher (A2) emissions pathways are interpreted by two global climate models. The higher the vulnerability index (computed by multiplying percentage decrease of groundwater recharge by a sensitivity index), the higher the vulnerability. The index is only defined for areas where groundwater recharge is projected to decrease by at least 10% relative to 1961-1990 (Döll, 2009).

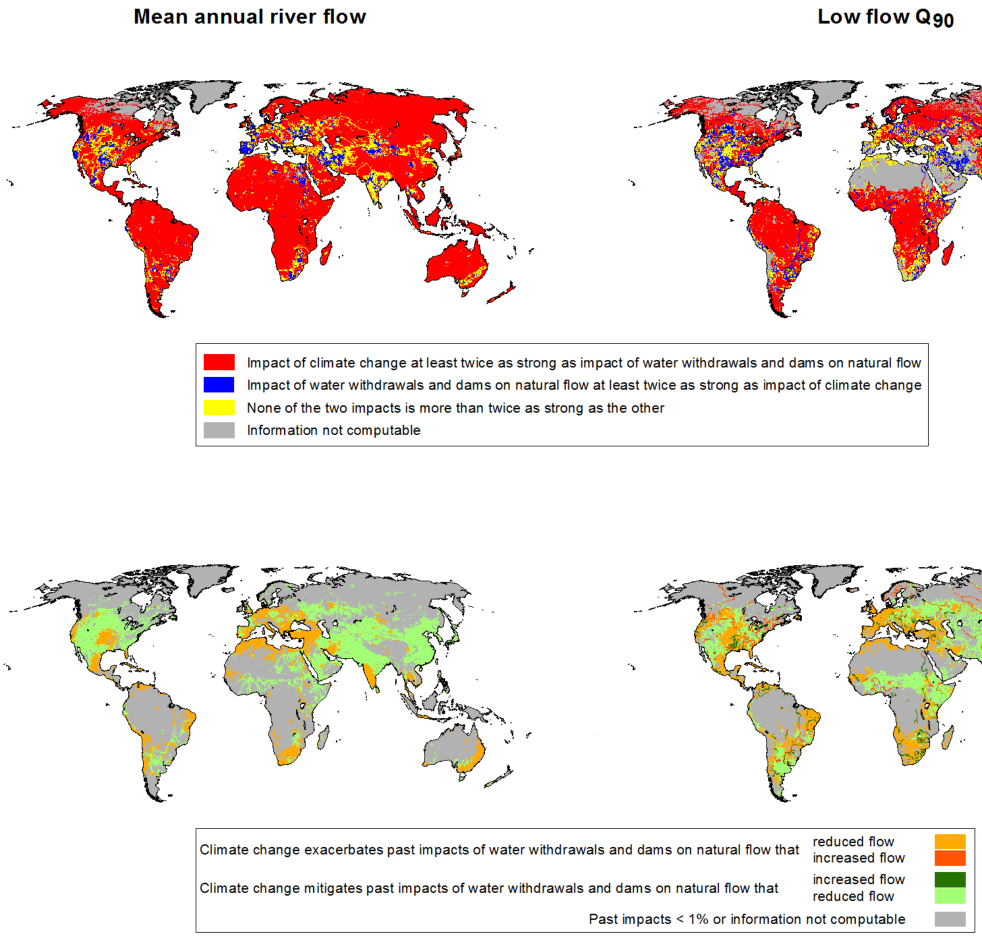


Figure RF-1: Impact of climate change relative to the impact of water withdrawals and dams on natural flows for two ecologically relevant river flow characteristics (mean annual river flow and monthly low flow Q_{90}), computed by a global water model (Döll and Zhang, 2010). Monthly Q_{90} was defined as the flow that is exceeded in 9 out 10 months. 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. Please note that the figure does not reflect spatial differences in the magnitude of change.
[Illustration to be redrawn to conform to IPCC publication specifications.]

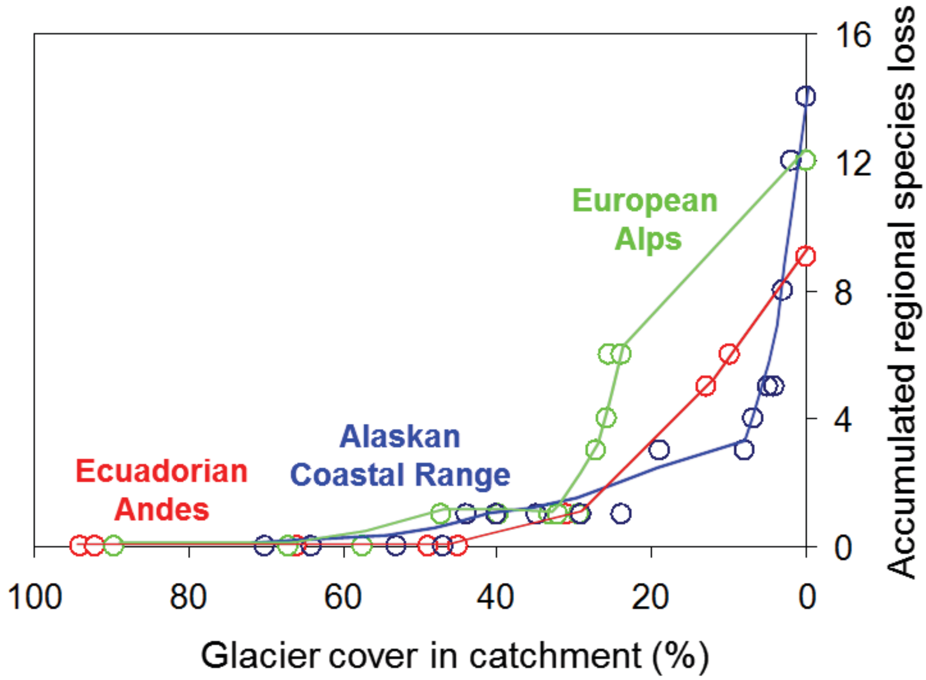


Figure RF-2: Accumulated loss of regional species richness (gamma diversity) of macroinvertebrates as a function of glacial cover in catchment. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%, and 9-14 species are predicted to be lost with the complete disappearance of glaciers in each region, corresponding to 11, 16 and 38% of the total species richness in the three study regions in Ecuador, Europe and Alaska. Data are derived from multiple river sites from the Ecuadorian Andes and Swiss and Italian Alps, and a temporal study of a river in the Coastal Range Mountains of southeast Alaska over nearly three decades of glacial shrinkage. Each data point represents a river site or date (Alaska), and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.

[Illustration to be redrawn to conform to IPCC publication specifications.]

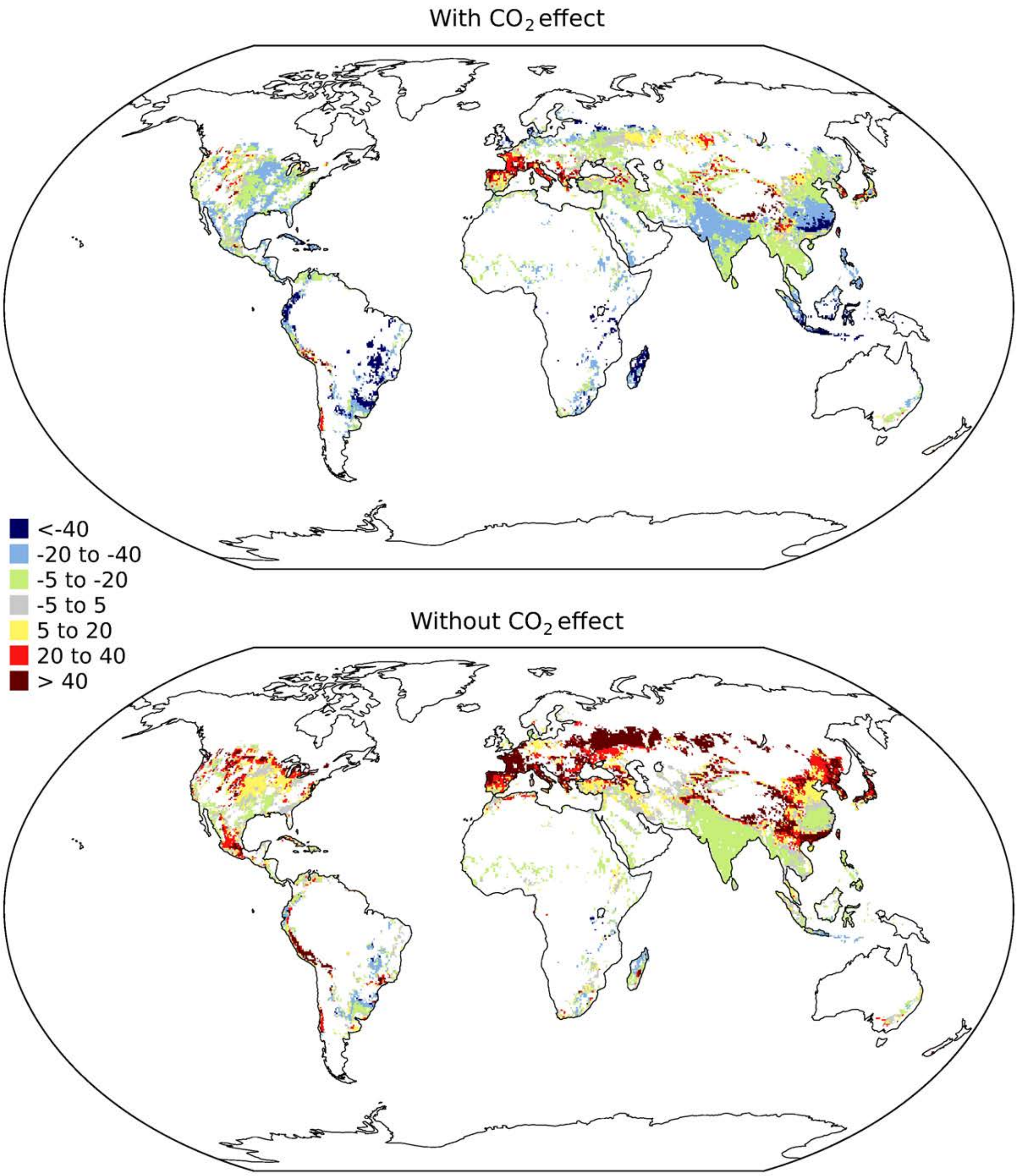


Figure VW-1: Percentage change in net irrigation requirements of 11 major crops from 1971–2000 to 2070–2099 on areas currently equipped for irrigation, assuming current management practices. Top: impact of climate change including physiological and structural crop responses to increased atmospheric CO_2 concentration (maximum effect in the absence of co-limitation by nutrients). Bottom: impact of climate change only. Shown is the median change derived from climate change projections by 19 GCMs (based on the SRES A2 emissions scenario) used to force a vegetation and hydrology model. Modified after Konzmann *et al.* (2013).
[Illustration to be redrawn to conform to IPCC publication specifications.]

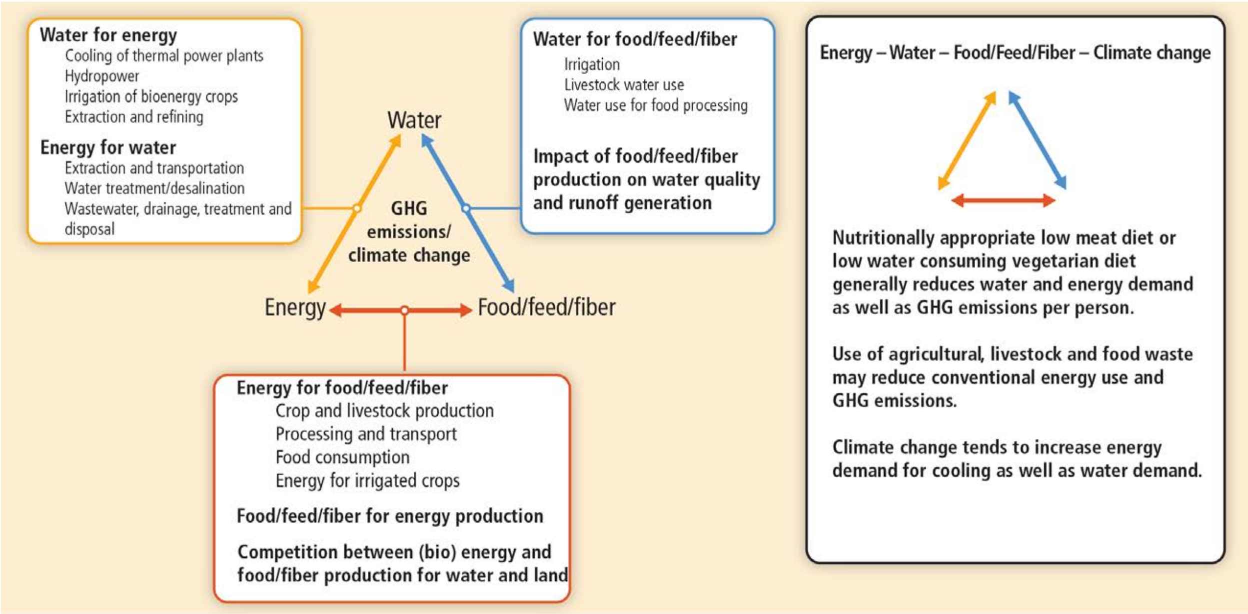


Figure WE-1: The water-energy-food nexus as related to climate change. The interlinkages of supply/demand, quality and quantity of water, energy and food/feed/fiber with changing climatic conditions have implications for both adaptation and mitigation strategies.