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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 (GHG) concentrations (*robust evidence, high agreement*). {3.4, 3.5} Modeling 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} For each degree of global warming, approximately 7% of the global population is projected to be exposed to a decrease of renewable water resources of at least 20% (multi-model mean). By the end of the 21st century, the number of people exposed annually to the equivalent of a 20th-century 100-year river flood is projected to be three times greater for very high emissions (Representative Concentration Pathway 8.5 (RCP8.5)) than for very low emissions (RCP2.6) (multi-model mean) for the fixed population distribution at the level in the year 2005. {Table 3-2, 3.4.8}

Climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions (*robust evidence, high agreement*). {3.4, 3.5} **This will intensify competition for water among agriculture, ecosystems, settlements, industry, and energy production, affecting regional water, energy, and food security (*limited evidence, medium to high agreement*).** {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 GHG 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 (*limited evidence, medium agreement*). Flood hazards are projected to increase in parts of South, Southeast, and Northeast Asia; tropical Africa; and South America (*limited evidence, medium agreement*). Since the mid-20th century, socioeconomic 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 (*limited evidence, medium agreement*). {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 the 21st century under the RCP8.5 scenario (*medium confidence*). {WGI AR5 Chapter 12} **This is *likely* to increase the frequency of short hydrological droughts (less surface water and groundwater) in these regions (*medium evidence, medium agreement*).** {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 (*medium evidence, high agreement*). 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 owing 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 (*medium evidence, high agreement*). 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 (*robust evidence, high agreement*). {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 (*robust evidence, high agreement*). 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 (*limited evidence, medium agreement*). 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 (*medium evidence, high agreement*). 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 (*limited evidence, high agreement*). 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 (*limited evidence, high agreement*). 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 GHG emissions imply risks for freshwater systems (*medium evidence, high agreement*). 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.

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 due mainly to increases in temperature and sea level, local changes of precipitation, and changes in the variability of those quantities.
- Semiarid 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, based mainly 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 AR5 Chapter 4 for freshwater in cold regions and WGI AR5 Chapters 10 for detection and attribution, 11 for near-term projections, and 12 for long-term projections of climate change. In this Working Group II contribution, impacts on aquatic ecosystems are discussed in Chapter 4 (see also Section 3.5.2.4). 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 to 30. Sections 3.2.7, 3.4.8, and 3.6.3 discuss impact 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

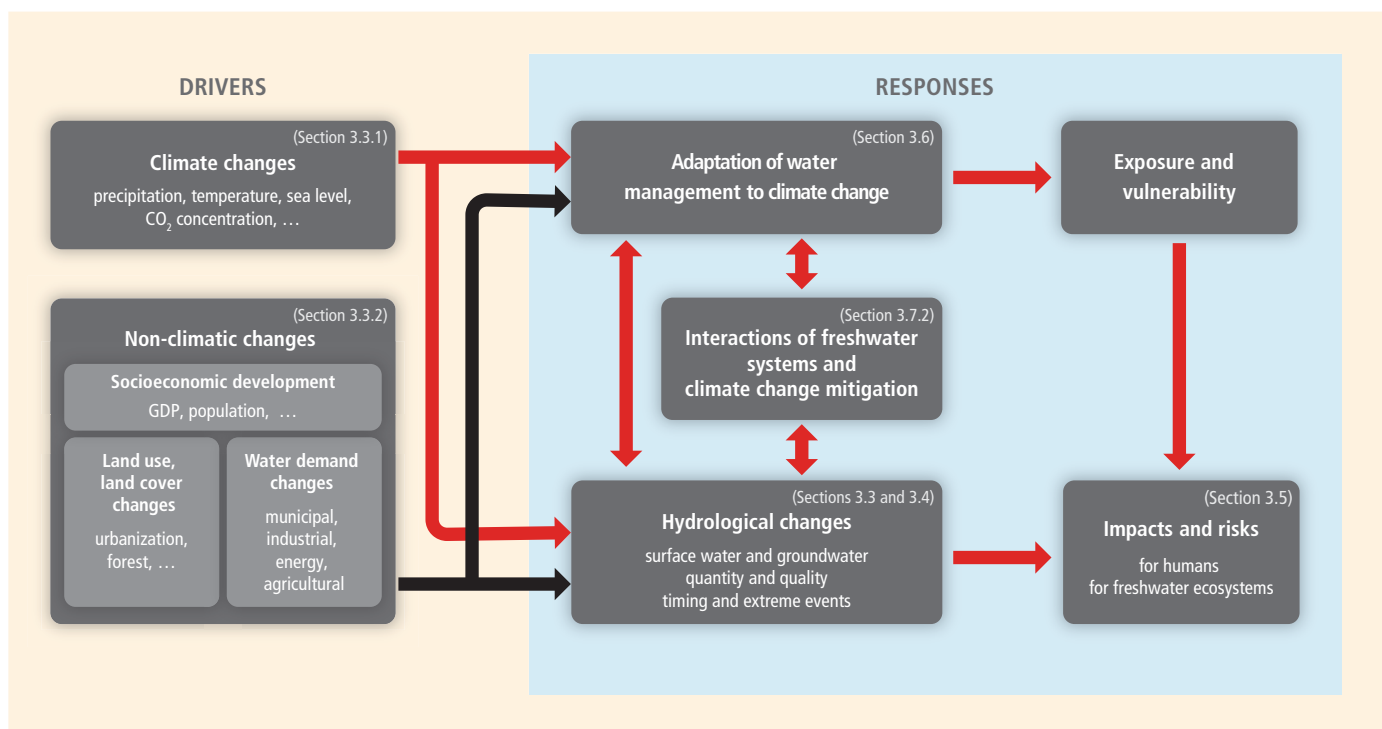
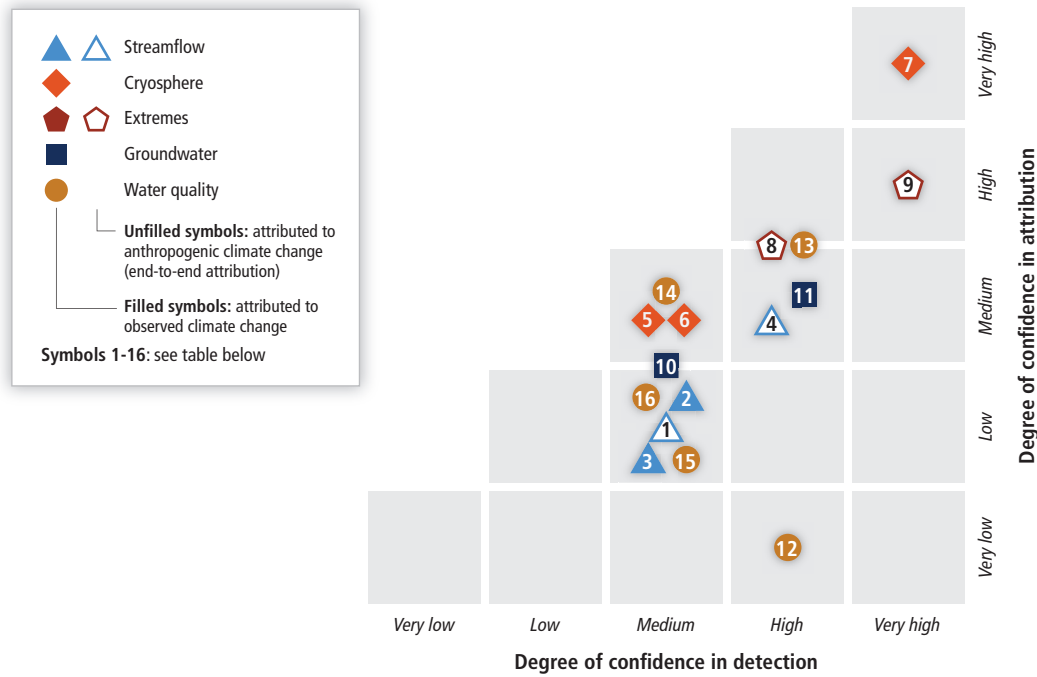


Figure 3-1 | Framework (boxes) and linkages (arrows) for considering impacts of climatic and social changes on freshwater systems, and consequent impacts on and risks for humans and freshwater ecosystems. Both climatic (Section 3.3.1) and non-climatic (Section 3.3.2) drivers have changed natural freshwater 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).

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.



	Observed change	Attributed to	Reference
1	Changed runoff (global, 1960–1994)	Mainly climatic change, and to a lesser degree CO ₂ increase and land use change	Gerten et al. (2008); Piao et al. (2007); Alkama et al. (2011)
2	Reduced runoff (Yellow River, China)	Increased temperature; only 35% of reduction attributable to human withdrawals	Piao et al. (2010)
3	Earlier annual peak discharge (Russian Arctic, 1960–2001)	Increased temperature and earlier spring thaw	Shiklomanov et al. (2007)
4	Earlier annual peak discharge (Columbia River, western USA, 1950–1999)	Anthropogenic warming	Hidalgo et al. (2009)
5	Glacier meltwater yield greater in 1910–1940 than in 1980–2000 (European Alps)	Glacier shrinkage forced by comparable warming rates in the two periods	Collins (2008)
6	Decreased dry-season discharge (Peru, 1950s–1990s)	Decreased glacier extent in the absence of a clear trend in precipitation	Baraer et al. (2012)
7	Disappearance of Chacaltaya Glacier, Bolivia (2009)	Ascent of freezing isotherm at 50 meters per decade, 1980s–2000s	Rosenzweig et al. (2007)
8	More intense extremes of precipitation (northern tropics and mid-latitudes, 1951–1999)	Anthropogenic greenhouse gas emissions	Min et al. (2011)
9	Fraction of risk of flooding (England and Wales, autumn 2000)	Extreme precipitation attributable to anthropogenic greenhouse radiation	Pall et al. (2011)
10	Decreased recharge of karst aquifers (Spain, 20th century)	Decreased precipitation, and possibly increased temperature; multiple confounding factors	Aguilera and Murillo (2009)
11	Decreased groundwater recharge (Kashmir, 1985–2005)	Decreased winter precipitation	Jeelani (2008)
12	Increased dissolved organic carbon in upland lakes (UK, 1988–2003)	Increased temperature and precipitation; multiple confounding factors	Evans et al. (2005)
13	Increased anoxia in a reservoir, moderated during ENSO (El Niño-Southern Oscillation) episodes (Spain, 1964–1991 and 1994–2007)	Decreased runoff due to decreased precipitation and increased evaporative demand	Marcé et al. (2010)
14	Variable fecal pollution in a saltwater wetland (California, 1969–2000)	Variable storm runoff; 70% of coliform variability attributable to variable precipitation	Pednekar et al. (2005)
15	Nutrient flushing from swamps, reservoirs (North Carolina, 1978–2003)	Hurricanes	Paerl et al. (2006)
16	Increased lake nutrient content (Victoria, Australia, 1984–2000)	Increased air and water temperature	Tibby and Tiller (2007)

of the documented change is not due to natural variability of the water cycle (Chapter 18; WGI AR5 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 multistep attribution, in which hydrological changes are shown to result from climatic changes that may in turn result partly from human activities.

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 $F = r_{expt}/r_{ctrl}$. 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 is 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 threefold, 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 AR5 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 AR5 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, diurnal temperature range, aerosol concentration, (net) solar radiation, vapor 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 (Gemmer et al., 2011; Fischer et al., 2013), 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 AR5 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 greenhouse gases (GHGs) due to permafrost degradation can have unprecedented impacts on the climate, but these processes are not yet well represented in global climate models (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 U.S. 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 River 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 streamflow 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 carbon dioxide (CO₂) concentration remains disputed (Box CC-VW).

In regions with seasonal snow storage, warming since the 1970s has led to earlier spring discharge maxima (*robust evidence, high agreement*) 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 owing 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 owing 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 also 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

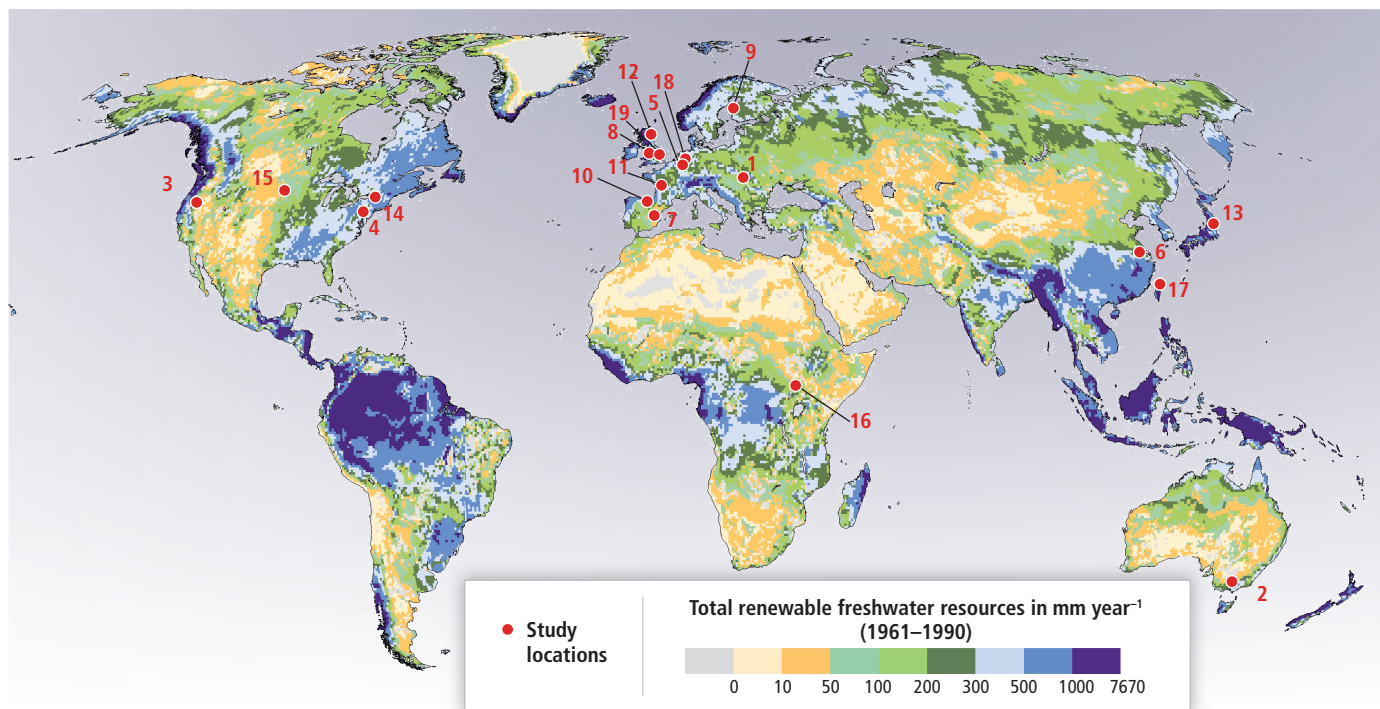
Most observed changes of water quality due to climate change (Table 3-1; Figure 3-2) are known from isolated studies, mostly of rivers or lakes in high-income countries, of a small number of variables. In addition, even though some studies extend over as many as 80 years, most are short term. For lakes 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 (*medium to robust evidence, high agreement*). Increased runoff results in greater loads of salts, fecal coliforms, pathogens, and heavy metals (Pednekar et al., 2005; Paerl et al., 2006; Tibby and Tiller, 2007; Boxall et al., 2009) (*robust evidence, medium to high agreement*, 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 (*robust evidence, medium to high agreement*) (Boxall et al., 2009; Loos et al., 2009; Benítez-Gilabert et al., 2010; Gascuel-Oudoux et al., 2010; Howden et al., 2010; Saarinen et al., 2010; Tetzlaff et al., 2010; Macleod et al., 2012). 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 (Ozaki et al., 2003; Chang, 2004; Benítez-Gilabert et al., 2010) (*limited evidence, medium agreement*). Studies of impacts on groundwater quality are limited and mostly report elevated concentrations of fecal coliforms during the rainy season or after extreme rain events (*medium evidence, high agreement*), with varying response times (Curriero et al., 2001; Tumwine et al., 2002, 2003; Auld et al., 2004; Jean et al., 2006; Seidu et al., 2013). 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 (*limited evidence, medium agreement*). 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*; Senhorst and Zwolsman, 2005; Whitehead et al., 2009a; Benítez-Gilabert et al., 2010; Howden et al., 2010; Kundzewicz and Krysanova, 2010; Ventela et al., 2011).

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 (Nyman et al., 2011; Bussi et al., 2013). 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 (Wang et al., 2007; Miao et al., 2011). 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 $3 \pm 2\%$; most of the decline in its lower reaches was due to dam construction (Three Gorges Dam) and soil conservation measures.



	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 interannual distribution of the mean monthly discharge.	Pekarova et al. (2008)
2	Purrumbete, Colac and 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, USA	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, USA	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 <i>Microcystis</i> 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 due to rainfall variations, acid deposition, land use, and CO ₂ enrichment.	Evans et al. (2005)
9	Coastal rivers from western Finland	1913–2007 1961–2007	Low pH values are associated with higher rainfall and river discharge in an acid sulfate soil basin. Critical values of dissolved organic carbon is associated with higher rainfall and river discharge.	Saarinen et al. (2010)
10	15 pristine mountain rivers, northern Spain	1973–2005	For a semiarid area, there is a clear relationship between increases in air temperature and a higher nutrient and dissolved organic carbon content.	Benítez-Gilbert et al. (2010)
11	30 coastal rivers and groundwater of western France	1973–2007 (2–6 years)	Interannual 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 fecal pollution are 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 are associated with increases in ambient temperature. Precipitation increases and variations are associated with an increase in the organic matter, sediments, and chemical oxygen demand content in water.	Ozaki et al. (2003)
14	Conestoga River Basin, Pennsylvania, USA	1977–1997	There is a close association between annual loads of total nitrogen and annual precipitation increases.	Chang (2004)
15	USA	1948–1994	Increased rainfall and runoff are associated with site-specific outbreaks of waterborne disease.	Curriero et al. (2001)
16	Northern and eastern Uganda	1999–2001, 2004, 2007	Elevated concentrations of fecal coliforms are 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 ⁻¹ . 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.

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 has changed over past decades (Huggel et al., 2012), even in regions with relatively complete event records (e.g., Switzerland; Hilker et al., 2009). Increased landslide impacts (measured by casualties or losses) in south and Southeast Asia, where landslides are triggered predominantly by monsoon and tropical cyclone activity, are largely attributed to population growth leading to increased exposure (Petley, 2012).

In summary, there is *limited evidence* and *low agreement* 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 (Mudelsee et al., 2003; Stahl et al., 2010; Benito and Machado, 2012; Hannaford and Hall, 2012), 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 (Petrow and Merz, 2009; Giuntoli et al., 2012; Hattermann et al., 2012), 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 (Bhutiyan 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 toward 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 (Wilson et al., 2010; Dahlke et al., 2012). 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 favorable 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).

Socioeconomic 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 US\$7 billion per year in the 1980s to about US\$24 billion per year in 2011 (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 1970, the annual number of flood-related deaths has been in the thousands, with more than 95% in developing countries (Handmer et al., 2012). There is *high confidence (medium evidence, high agreement)* 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; Hilker et al., 2009; Benito and Machado, 2012), although there are exceptions (Jiang et al., 2005; Chang et al., 2009).

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, Standardized Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), Standardized 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 AR5 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 toward lower summer minimum flows for 1962–2004 in small catchments in southern and Eastern Europe, 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 El Niño-

Southern Oscillation (ENSO) 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 AR5 Chapter 2). Among other climatic drivers are atmospheric CO₂, 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 modeling of the atmospheric response to external forcing, and the external forcing itself as described by the Representative Concentration Pathways (RCPs; Section 1.1.3). Internal variability and variation between models account for all of the uncertainty in precipitation in the first few decades of the 21st century in Coupled Model Intercomparison Project Phase 3 (CMIP3) 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 AR5 Chapter 11) is due mostly to divergent scenarios.

CMIP5 simulations of the water cycle during the 21st century (WGI AR5 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 (*very high confidence*), probably by about 1.5 times more over land than over ocean.
- 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 AR5 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 (WGI AR5 Figure 12-25). 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*; WGI AR5 Figure 12-23; WGI AR5 Section 12.4.5.3).

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 (Utsumi et al., 2011; Berg et al., 2013). Annual maxima of daily precipitation that are observed to have 20-year return periods in 1986–2005 are projected to have 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 to 2.5% K⁻¹, the 20-year return amount of daily precipitation typically increases at 4 to 10% K⁻¹. Agreement between model-simulated extremes and reanalysis extremes is good in the extratropics 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, socioeconomic, and technological changes, including lifestyle changes. These change both exposure to hazard and requirements for water resources. A wide range of socioeconomic 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 socioeconomic 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).

Owing 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 owing 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., Chiew et al., 2009; Gosling et al., 2010; Arnell, 2011; Bae et al., 2011; Jackson et al., 2011; Olsson et al., 2011; Kling et al., 2012; Arnell and Gosling, 2013). 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; Manning et al., 2009; Christerson et al., 2012; Liu et al., 2013). 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 used only 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 (Quintana Segui et al., 2010; Chen J. et al., 2011). 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 (van Pelt et al., 2009; Piani et al., 2010; 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 depends largely 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 (Steele-Dunne et al., 2008; Cloke et al., 2010; Vaze et al., 2010; Arnell, 2011; Lawrence and Haddeland, 2011). 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), owing 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 that would be critical for a system and then uses a hydrological model to determine the meteorological conditions that 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,b). 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 characterize 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 shows 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 AR5 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 CO₂ 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

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 5 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

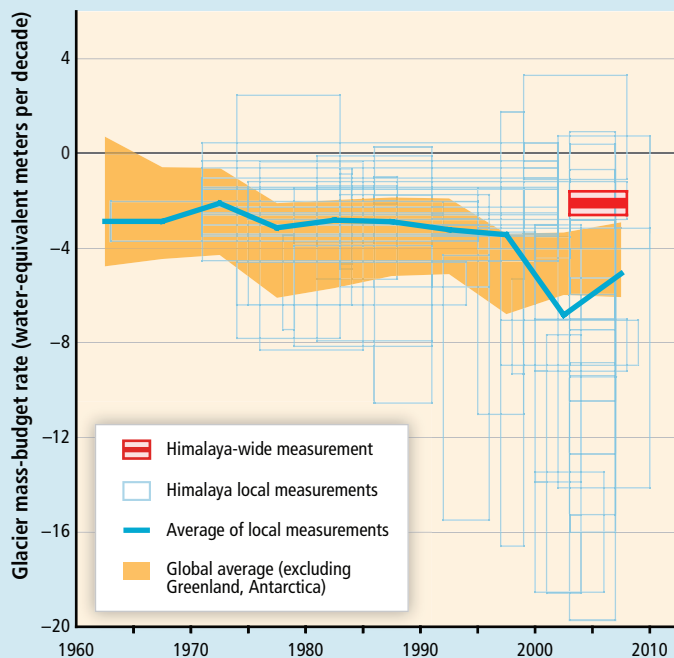


Figure 3-3 | All published glacier mass balance measurements from the Himalaya (based on Bolch et al., 2012). To emphasize the variability of the raw information, each measurement is shown as a box of height ± 1 standard deviation centred on the average balance (± 1 standard error for multiannual measurements). Region-wide measurement (Kääb et al., 2012) was by satellite laser altimetry. Global average (WGI AR5 Chapter 4) is shown as a 1-sigma confidence region.

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 to 200 mm yr⁻¹ 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 afterward (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.

water balance. It suggests strongly that the conventional measurements, mostly on small, accessible glaciers, are not regionally representative.

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 to 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 overcompensates for the loss of ice.

risk of extreme hot days (Seneviratne et al., 2006; Hirschi et al., 2011) and heat waves. For a range of scenarios, soil moisture droughts lasting 4 to 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 the 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 (WGI AR5 Figure 4-18). Under RCP2.6, the permafrost area is projected to stabilize at near 37% less than the 20th century area.

3.4.3. Glaciers

All projections for the 21st century (WGI AR5 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 toward 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 about 105 km² 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 be dated only 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.

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., Hirabayashi et al., 2008; Döll and Zhang, 2010; Fung et al., 2011; Murray et al., 2012; Okazaki et al., 2012; Tang and Lettenmaier, 2012; Weiland et al., 2012a; Arnell and Gosling, 2013; Nakaegawa et al., 2013; Schewe et al., 2013). 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 driven largely 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°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 AR5 Figure 12-24, largely because it is based on fewer climate models.

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°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°C rise in temperature. In the Mitano catchment in Uganda, for example, there is a nonlinear 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.

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 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 that currently experience considerable snowfall, where the marginal effect of higher temperatures on snowfall and snowmelt 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

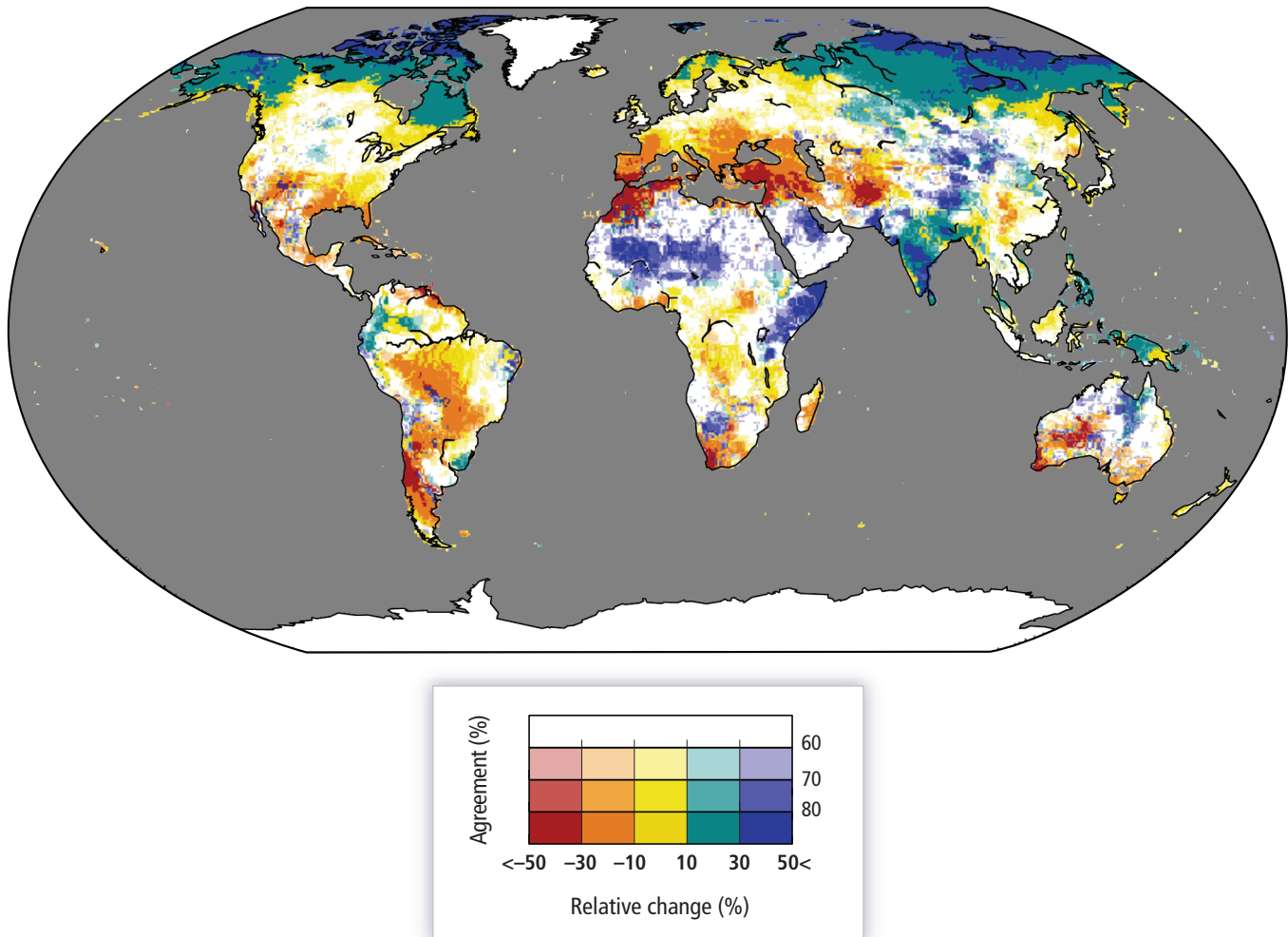


Figure 3-4 | Percentage change of mean annual streamflow for a global mean temperature rise of 2°C above 1980–2010 (2.7°C above pre-industrial). Color hues show the multi-model mean change across 5 General Circulation Models (GCMs) and 11 Global Hydrological Models (GHMs), and saturation shows the agreement 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).

(Green et al., 2011; Taylor R. et al., 2013a) has increased significantly since then. Ensemble studies, relying on between 4 and 20 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 semiarid High Plains aquifer of the USA (Ng et al., 2010; Crosbie et al., 2013b). 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 CO₂ 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 owing to exceedance of the infiltration capacity (typically in humid areas), or may increase it owing to faster percolation through the root zone and thus reduced evapotranspiration (typically in semiarid 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 (van Roosmalen et al., 2007; Crosbie et al., 2013b). The sensitivity of groundwater recharge change to precipitation change was found to be highest for low groundwater

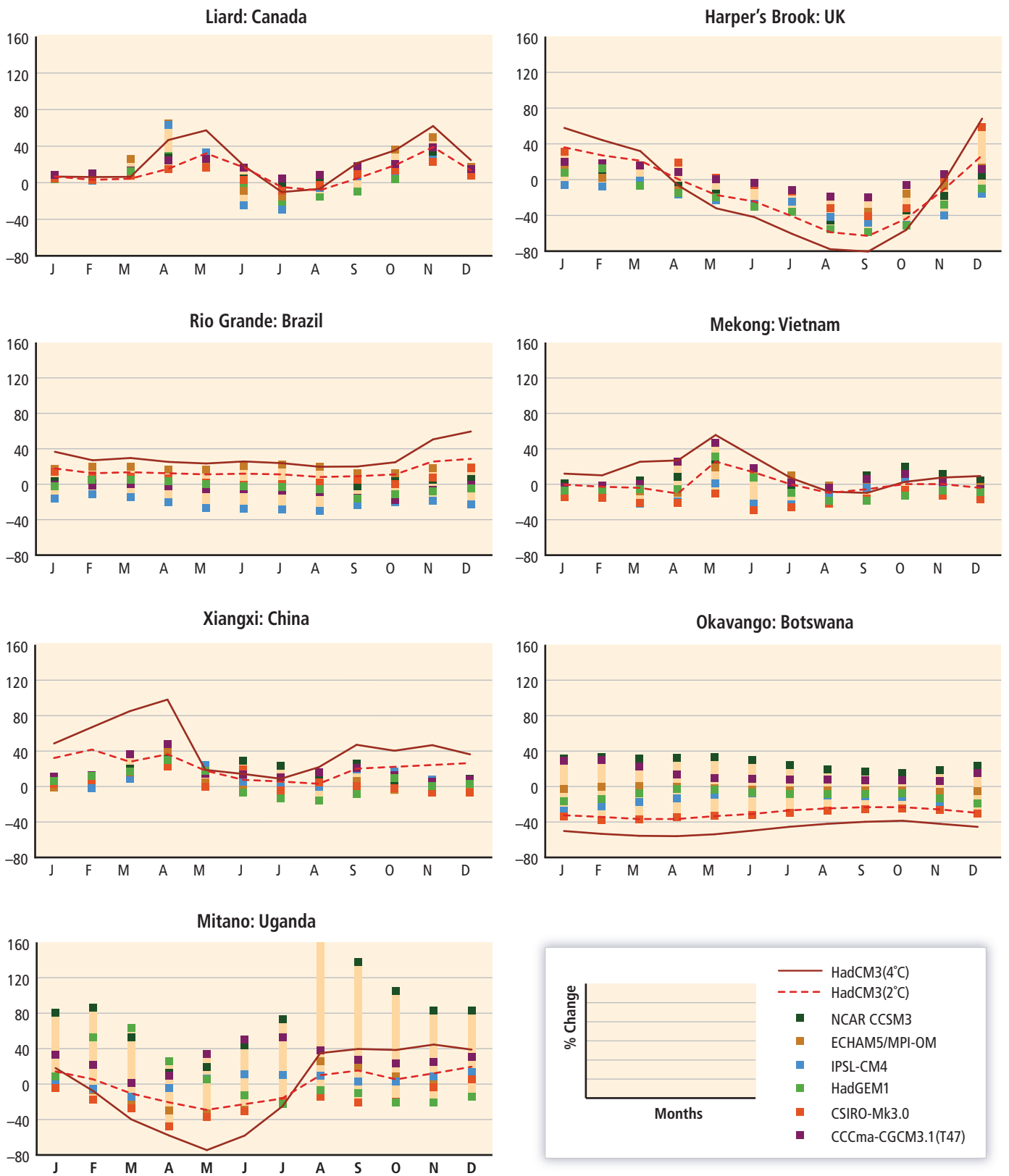


Figure 3-5 | Change in mean monthly runoff across seven climate models in seven catchments, with a 2°C increase in global mean temperature above 1961–1990 (Kingston and Taylor, 2010; Arnell, 2011; Hughes et al., 2011; Kingston et al., 2011; Nobrega et al., 2011; Thorne, 2011; Xu et al., 2011). One of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

recharge and lowest for high groundwater recharge, the ratio of recharge change to precipitation change ranging from 1.5 to 6.0 in the semiarid 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 to 70% of groundwater recharge, although only 25 to 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. Although 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 m, the thickness of the unconfined freshwater layer decreases by roughly 40 m (Ghyben-Herzberg relation). Deltas are also affected by storm surges that drive saltwater 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). Saltwater 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 semiarid areas where the groundwater table is within 2 to 10 m of the surface (Jiang et al., 2009; Ferguson and Maxwell, 2010).

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 (Arheimer et al., 2005; Andersen et al., 2006; Wilby et al., 2006; Ducharne, 2008; Marshall and Randhir, 2008; Bonte and Zwolsman, 2010; Towler et al., 2010; Trolle et al., 2011;

Rehana and Mujumdar, 2012). 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 (1) local conditions; (2) climatic and environmental assumptions; and (3) the current or reference pollution state (Chang, 2004; Whitehead et al., 2009a,b; Bonte and Zwolsman, 2010; Kundzewicz and Krysanova, 2010; Sahoo et al., 2010; Trolle et al., 2011). 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 (Brikowski, 2008; Ducharne, 2008; Marshall and Randhir, 2008; Loos et al., 2009; Bonte and Zwolsman, 2010; Qin et al., 2010; Sahoo et al., 2010; Trolle et al., 2011), rivers (Andersen et al., 2006; Whitehead et al., 2009a,b; Bowes et al., 2012) 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; WGIAR5 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 CO₂ 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 to 50% in Australia and Africa (Yang et al., 2003). The largest increases are expected in semiarid areas, where extreme events may contribute about half of total erosion; for instance, in Mediterranean Spain 43% of sediment yield over the time period 1990–2009 was produced by a single event (Bussi et al., 2013). In agricultural lands in temperate regions, soil erosion may respond to more intense erosion in complex nonlinear 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 2070–2099 projected a decrease of rainfall by 10 to 14% in erosion-sensitive months and thus a decline in soil erosion by 11 to 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 to 195% of soil loss during 2010–2039 under conventional tillage, for three emission scenarios (*Special Report on Emission Scenarios* (SRES) A2 and B2, and IS92a), whereas under conservation tillage they show decreases of 26 to 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 to 14% in two Danish rivers under the SRES A2 emission scenario was projected to increase the annual suspended sediment load by 9 to 36% 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

Frequently Asked Questions

FAQ 3.1 | How will climate change affect the frequency and severity of floods and droughts?

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 Southeast 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.

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 to 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 owing to the nonlinear 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 *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX; 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 owing to variation between climate models and their coupling to hydrological models.

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 AR5 Chapter 12; Vidal et al., 2012; Orłowsky and Seneviratne, 2013), 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 characterize "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 to 30% of the land surface (excluding cold areas) experienced a significant increase in the frequency of 3-month hydrological droughts, while about 15 to 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),

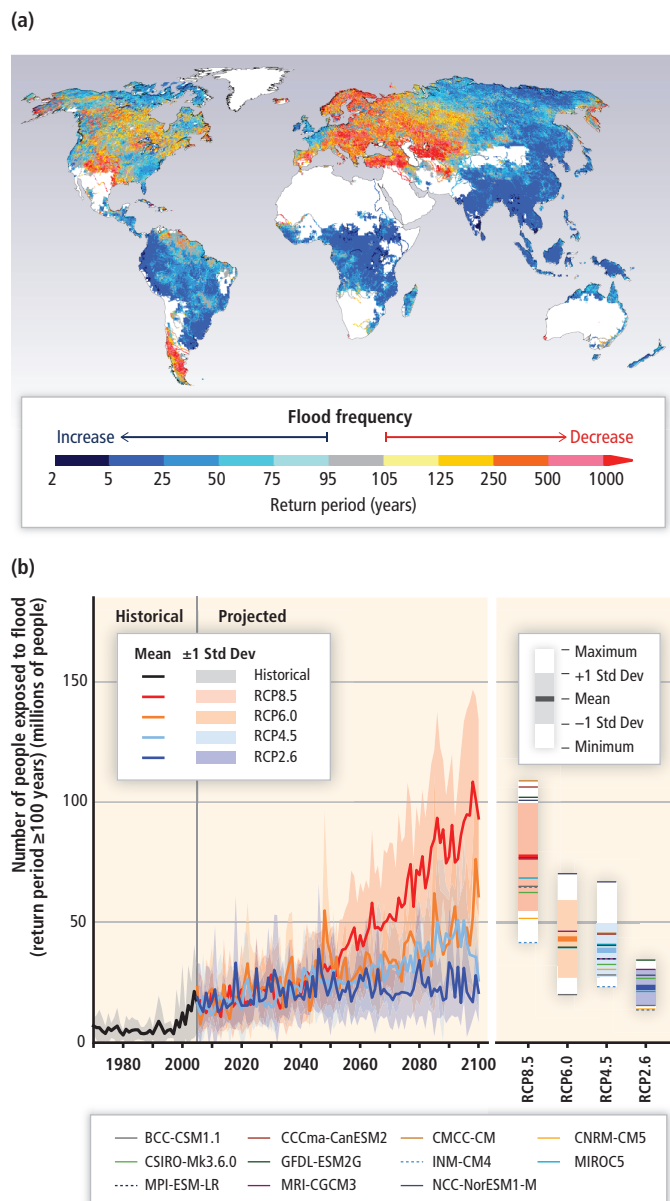


Figure 3-6 | (a) Multi-model median return period (years) in the 2080s for the 20th century 100-year flood (Hirabayashi et al., 2013), based on one hydrological model driven by 11 Coupled Model Intercomparison Project Phase 5 (CMIP5) General Circulation Models (GCMs) under Representative Concentration Pathway 8.5 (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. Regions with mean runoff less than 0.01 mm day⁻¹, Antarctica, Greenland, and Small Islands are excluded from the analysis and indicated in white. (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 (extent of white), mean (thick colored lines), ± 1 standard deviation (extent of shading), and projections of each GCM (thin colored lines) 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 to 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 to 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 to 25, depending on the RCP, with strong increases in Asia and Africa due to high population growth.

short hydrological droughts are projected to increase in frequency while 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, owing 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. Studies of projected flood damages are mainly focused in Europe, the USA, and Australia (Handmer et al., 2012; Bouwer, 2013). 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 preindustrial 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).

3.5.1. Availability of Water Resources

About 80% of the world's population already suffers serious threats to its water security, as measured by indicators including water availability,

Table 3-2 | Effects of different greenhouse gas (GHG) emissions scenarios on hydrological changes and freshwater-related impacts of climate change on humans and ecosystems. Among the Special Report on Emission Scenarios (SRES) scenarios, GHG emissions are highest in A1f and A2, lower in A1 and B2, and lowest in B1. Representative Concentration Pathway 8.5 (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 Coupled Model Intercomparison Project Phase 5 (CMIP5) model mean) over different reference periods, typically since pre-industrial. GW since pre-industrial is projected to be, for RCP8.5, approximately 2°C in the 2040s and 4°C in the 2090s. For RCP6.0, GW is 2°C in the 2060s and 2.5°C in the 2090s, while in RCP2.6, GW stays below 1.5°C throughout the 21st century (Figure 1-4 in Chapter 1). Population scenario SSP2 assumes a medium population increase. The number of GCMs that were used in the studies is provided.

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 General Circulation Models (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)	<ul style="list-style-type: none"> • 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)	<ul style="list-style-type: none"> • 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)	<ul style="list-style-type: none"> • RCP2.6: –0.2 to 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)	<ul style="list-style-type: none"> • 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 yr ⁻¹ of per capita blue water resources 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 yr ⁻¹ of per capita blue water resources) (median of 19 GCMs, population constant at 2000 values)	<ul style="list-style-type: none"> • 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 yr ⁻¹ of per capita blue water resources) exposed to an increase in stress (1 GCM)	For emissions scenarios with 2°C target, compared to SRES A1: <ul style="list-style-type: none"> • 5–8% impact reduction in 2050 • 10–20% reduction in 2100 	Arnell et al. (2013)
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)	<ul style="list-style-type: none"> • 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)	<ul style="list-style-type: none"> • 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 L ⁻¹) (2) Maximum duration of MAC exceedance (2050, 1 GCM)	<ul style="list-style-type: none"> • 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)	<ul style="list-style-type: none"> • 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)	<ul style="list-style-type: none"> • 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)	<ul style="list-style-type: none"> • SRES B2: (1) 14–15 billion € yr⁻¹, (2) 440,000–470,000 people • SRES A2: (1) 18–21 billion € yr⁻¹, (2) 510,000–590,000 people • Reference period: (1) 6.4 billion € yr⁻¹, (2) 200,000 people 	Feyen et al. (2012)



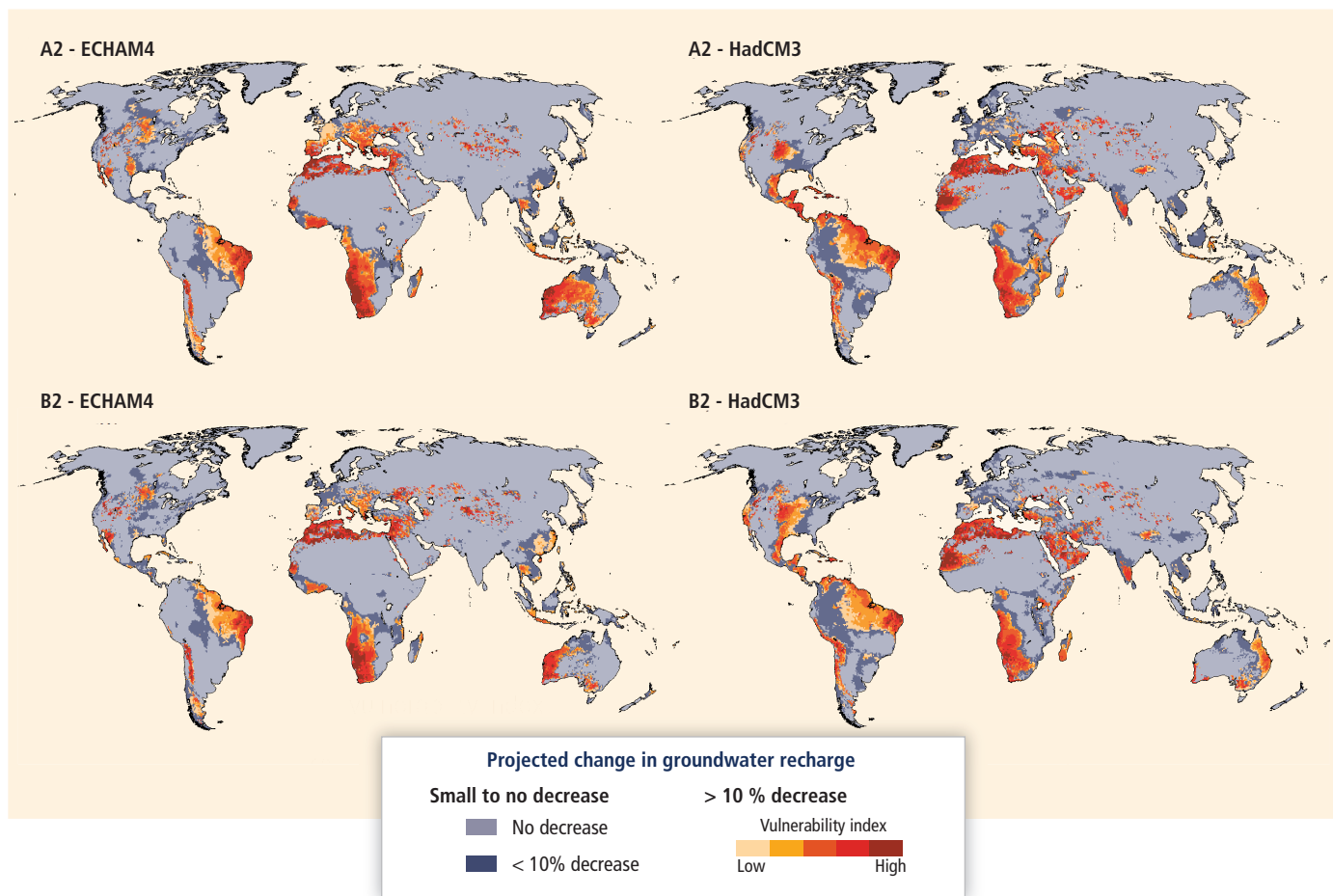


Figure 3-7 | Human vulnerability to climate change–induced decreases of renewable groundwater resources by the 2050s. Lower (Special Report on Emission Scenarios (SRES) B2) and higher (SRES A2) emissions pathways are interpreted by two global climate models. The higher the vulnerability index (computed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

water demand, and pollution (Vörösmarty et al., 2010). Climate change can alter the availability of water and therefore threaten water security as defined by UNESCO (2011).

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 (Hayashi et al., 2010; Arnell et al., 2011, 2013; Fung et al., 2011; Murray et al., 2012; Gerten et al., 2013; Gosling and Arnell, 2013; 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 that 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°C above preindustrial, 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 about 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°C rise in global mean temperature (compared to the 1990s), rising to 14% at 2°C and 17% at 3°C; the spread across climate and hydrological models was, however, large.

Under climate change, reliable surface water supply is expected to decrease due to increased variability of river flow that is due in turn to

Frequently Asked Questions

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

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.

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 sustainable only 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 to 39%) for RCP2.6 to 38% (range 27 to 50%) for RCP8.5 (Portmann et al., 2013; see also 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, 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 to 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 be explained partly 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 CO₂ concentration (CO₂ fertilization) might partly cancel out the adverse effects of climate change, potentially reducing global irrigation water demand (Konzmann et al., 2013; see also 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 CO₂ effects, that is, decreases in per-calorie water demand. The CO₂ 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 CO₂ 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 modeling 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; see also 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 3.2.6) 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 (Renofalt et al., 2010; Golombek et al., 2012). 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 owing 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, owing to increases in stream temperatures and the incidence of low flows (Flörke et al., 2012; van Vliet et al., 2012; see also Table 3-2). Warmer cooling water was computed to lower thermal power plant efficiency and thus electricity production by 1.5 to 3% in European countries by the 2080s under emissions scenario SRES 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; Jiménez, 2008; van Vliet and Zwolsman, 2008; Black and King, 2009; Brooks et al., 2009; Whitehead et al., 2009a; Bonte and Zwolsman, 2010; Hall and Murphy, 2010; Mukhopadhyay and Dutta, 2010; Qin et al., 2010; Chakraborti et al., 2011; Major et al., 2011; Thorne and Fenner, 2011; Christerson et al., 2012):

- 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 (Zwolsman et al., 2010; Arnell et al., 2011).

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,b; 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 fecal 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 composed 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 Section 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; see also 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 (Pinter et al., 2006; Koetse and Rietveld, 2009; Rabassa, 2009; Badjeck et al., 2010; Beniston, 2012). 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; Burke et al. 2009; Buhaug et al., 2010; 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). Although 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.

Frequently Asked Questions

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

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 reuse, 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.

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 program of adaptation typically mixes “hard” infrastructural and “soft” institutional measures (Bates et al., 2008; Cooley, 2008; Mertz et al., 2009; Sadoff and Muller, 2009; UNECE, 2009; Olhoff and Schaer, 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 16.4. 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 (Goulden et al., 2009; Engle and Lemos, 2010; Huntjens et al., 2010; Stuart-Hill and Schulze, 2010; Ziervogel et al., 2010; Wilby and Vaughan, 2011; Bergsma et al., 2012); 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 increasing. Changes in operating practices and infrastructure improvements could help California’s water managers respond to changes in the volume and timing of supply (Medellin-Azuara et al., 2008; Connell-Buck et al., 2011). 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 characterize the potential range of impacts on water resources and flooding. Others (e.g., Brekke et al., 2008; Lopez et al., 2009; Christerson et al., 2012; Hall et al., 2012) use very large numbers of scenarios to generate likelihood distributions of indicators of impact for use in risk assessment. However, it has been argued (Hall, 2007; Stainforth et al., 2007; Dessai et al., 2009) that attempts to construct probability distributions of impacts are misguided because of “deep” uncertainty, which arises because analysts do not know, or cannot agree on, 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 (Koutsoyiannis et al., 2008; Anagnostopoulos et al., 2010; Blöschl and Montanari, 2010; 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 (Koutsoyiannis et al., 2009, 2011; Huard, 2011); the critique also assumes that adaptation assessment procedures would use only 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 toward adaptive water management (Pahl-Wostl, 2007; Pahl-Wostl et al., 2008; Matthews and Wickel, 2009; Mysiak et al., 2009; Huntjens et al., 2012; Short et al., 2012; Gersonius et al., 2013) and the adoption of resilient or “no-regrets” approaches (WWAP, 2009; Henriques and Spraggs, 2011). 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, although 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

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

Category	Option	May assist both adaptation and mitigation
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 ^a 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	
	Promote switching to more appropriate crops (drought-resistant, salt-resistant; low water demand)	X
Plant flood- or drought-resistant crop varieties		
Agricultural irrigation	Improve irrigation efficiency and reduce demand for irrigation water	X
	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

^aThis includes water reuse, rain water harvesting, and desalination, among others.

Sources: Vörösmarty et al. (2000); Marsalek et al. (2006); Mogaka et al. (2006); Dillon and Jiménez (2008); Jiménez and Asano (2008); Keller (2008); McCafferty (2008); McGuckin (2008); Seah (2008); UN-HABITAT (2008); Thöle (2008); Andrews (2009); Bahri (2009); Munasinghe (2009); NACWA (2009); OFWAT (2009); Reiter (2009); Whitehead et al. (2009b); de Graaf and der Brugge (2010); Dembo (2010); Godfrey et al. (2010); Howard et al. (2010); Mackay and Last (2010); Mukhopadhyay and Dutta (2010); OECD (2010); Renofalt et al. (2010); Zwolsman et al. (2010); Arkell (2011a, 2011b); Elliott et al. (2011); Emelko et al. (2011); Jiménez (2011); Kingsford (2011); Major et al. (2011); Sprenger et al. (2011); UNESCO (2011); Wang X. et al. (2011); Bowes et al. (2012).

management that explicitly incorporates climate change and its uncertainty is the three-step framework of the U.S. 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 for the SRES A1B scenario (Kirshen, 2007). Including two further costs, for reservoir construction because 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 for the SRES A1B scenario (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\$19.7 billion for a dry GCM projection of the SRES A2 scenario and US\$14.4 billion for a wet GCM projection (Ward et al., 2010; World Bank, 2010). Annual urban infrastructure costs, primarily for wastewater treatment and urban drainage, were US\$13.0 billion (dry) and US\$27.5 billion (wet). Under both GCM projections for the A2 scenario, the water sector accounted for about 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 to 2.7 billion for current urban water infrastructure,

plus US\$1.0 to 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 US\$0.05 to 0.15 billion for existing facilities and US\$0.015 to 0.05 billion for new developments. For wastewater treatment, the equivalent estimates are US\$0.1 to 0.2 billion and US\$0.075 to 0.2 billion.

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).

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; Radic et al., 2013; Schewe et al., 2013; WGI AR5 Chapter 13.

Climate-related drivers of impacts			Level of risk & potential for adaptation																			
Warming trend	Drying trend	Extreme precipitation																				
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation																		
Flood risks associated with climate change increase with increasing greenhouse gas emissions. (<i>robust evidence, high agreement</i>) [3.4.8]	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).		<table border="1"> <tr> <td></td> <td>Very low</td> <td>Medium</td> <td>Very high</td> </tr> <tr> <td>Present</td> <td colspan="3">[Bar chart showing risk level]</td> </tr> <tr> <td>Near term (2030–2040)</td> <td colspan="3">[Bar chart showing risk level]</td> </tr> <tr> <td rowspan="2">Long term (2080–2100)</td> <td>2°C</td> <td colspan="2">[Bar chart showing risk level]</td> </tr> <tr> <td>4°C</td> <td colspan="2">[Bar chart showing risk level]</td> </tr> </table>		Very low	Medium	Very high	Present	[Bar chart showing risk level]			Near term (2030–2040)	[Bar chart showing risk level]			Long term (2080–2100)	2°C	[Bar chart showing risk level]		4°C	[Bar chart showing risk level]	
	Very low	Medium	Very high																			
Present	[Bar chart showing risk level]																					
Near term (2030–2040)	[Bar chart showing risk level]																					
Long term (2080–2100)	2°C	[Bar chart showing risk level]																				
	4°C	[Bar chart showing risk level]																				
Climate change is projected to reduce renewable water resources significantly in most dry subtropical regions. (<i>robust evidence, high agreement</i>) [3.5.1]	This will exacerbate competition for water among agriculture, ecosystems, settlements, industry and energy production, affecting regional water, energy, and food security.		<table border="1"> <tr> <td></td> <td>Very low</td> <td>Medium</td> <td>Very high</td> </tr> <tr> <td>Present</td> <td colspan="3">[Bar chart showing risk level]</td> </tr> <tr> <td>Near term (2030–2040)</td> <td colspan="3">[Bar chart showing risk level]</td> </tr> <tr> <td rowspan="2">Long term (2080–2100)</td> <td>2°C</td> <td colspan="2">[Bar chart showing risk level]</td> </tr> <tr> <td>4°C</td> <td colspan="2">[Bar chart showing risk level]</td> </tr> </table>		Very low	Medium	Very high	Present	[Bar chart showing risk level]			Near term (2030–2040)	[Bar chart showing risk level]			Long term (2080–2100)	2°C	[Bar chart showing risk level]		4°C	[Bar chart showing risk level]	
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Long term (2080–2100)	2°C	[Bar chart showing risk level]																				
	4°C	[Bar chart showing risk level]																				
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. (<i>robust evidence, high agreement</i>) [3.4.3]	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.		<table border="1"> <tr> <td></td> <td>Very low</td> <td>Medium</td> <td>Very high</td> </tr> <tr> <td>Present</td> <td colspan="3">[Bar chart showing risk level]</td> </tr> <tr> <td>Near term (2030–2040)</td> <td colspan="3">[Bar chart showing risk level]</td> </tr> <tr> <td rowspan="2">Long term (2080–2100)</td> <td>2°C</td> <td colspan="2">[Bar chart showing risk level]</td> </tr> <tr> <td>4°C</td> <td colspan="2">[Bar chart showing risk level]</td> </tr> </table>		Very low	Medium	Very high	Present	[Bar chart showing risk level]			Near term (2030–2040)	[Bar chart showing risk level]			Long term (2080–2100)	2°C	[Bar chart showing risk level]		4°C	[Bar chart showing risk level]	
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	4°C	[Bar chart showing risk level]																				

Frequently Asked Questions

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

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.

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 km²) 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 to 100% were computed, mostly in semiarid 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 (van Dijk and Keenan, 2007; Trabucco et al., 2008; 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 m 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 semiarid 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).

CO₂ leakage to freshwater aquifers from saline aquifers used for carbon capture and storage (CCS) can lower pH by 1 to 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 about 9000 to 30,000 m³ 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 to 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 to 3.1% of current global CO₂ 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 CO₂ storage in soils by reducing water stress and so enhancing biomass production. Irrigation in semiarid California did not significantly increase soil organic carbon (Wu et al., 2008). Water management in rice paddies can reduce methane (CH₄) emissions. If rice paddies are drained at least once during

the growing season, with resulting increased water withdrawals, global CH₄ emissions from rice fields could be decreased by 4.1 Tg yr⁻¹ (16% around the year 2000), and nitrous oxide (N₂O) 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 socioeconomic 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 (see Box CC-VW).

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. Moreover, the establishment of a proper baseline to isolate the effects derived from climate change from the anthropogenic cause 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.

References

- Adam, J.C., A.F. Hamlet, and D.P. Lettenmaier, 2009: Implications of global climate change for snowmelt hydrology in the twenty-first century. *Hydrological Processes*, **23**(7), 962-972.
- Aguilera, H. and J.M. Murillo, 2009: The effect of possible climate change on natural groundwater recharge based on a simple model: a study of four karstic aquifers in SE Spain. *Environmental Geology*, **57**(5), 963-974.
- Alkama, R., B. Decharme, H. Douville, and A. Ribes, 2011: Trends in global and basin-scale runoff over the late twentieth century: methodological issues and sources of uncertainty. *Journal of Climate*, **24**(12), 3000-3014.
- Allen, D.M., A.J. Cannon, M.W. Toews, and J. Scibek, 2010: Variability in simulated recharge using different GCMs. *Water Resources Research*, **46**, W00F03, doi:10.1029/2009WR008932.
- Anagnostopoulos, G.G., D. Koutsoyiannis, A. Christofides, A. Efstratiadis, and N. Mamassis, 2010: A comparison of local and aggregated climate model outputs with observed data. *Hydrological Sciences Journal*, **55**(7), 1094-1110.
- Andersen, H.E., B. Kronvang, S.E. Larsen, C.C. Hoffmann, T.S. Jensen, and E.K. Rasmussen, 2006: Climate-change impacts on hydrology and nutrients in a Danish lowland river basin. *Science of the Total Environment*, **365**(1-3), 223-237.
- Andrews, J., 2009: Towards 2030, Sydney's blueprint for development. *Urban World* **1**(5), 42-47.
- Arheimer, B., J. Andreasson, S. Fogelberg, H. Johnsson, C. Pers, and K. Persson, 2005: Climate change impact on water quality: Model results from southern Sweden. *Ambio*, **34**(7), 559-566.
- Arkell, B., 2011a: *Climate Change Implications for Water Treatment: Overview Report*. UK Water Industry Research, London, UK, 65 pp.
- Arkell, B., 2011b: *Climate Change Modelling for Sewerage Networks*. UK Water Industry Research, London, UK, 31 pp.
- Arndt, D.S., M.O. Baringer, and M.R. Johnson (eds.), 2010: State of the climate in 2009. *Bulletin of the American Meteorological Society*, **91**(7), S1-S224.
- Arnell, N.W., 2011: Incorporating climate change into water resources planning in England and Wales. *Journal of the American Water Resources Association*, **47**(3), 541-549.
- Arnell, N.W. and S.N. Gosling, 2013: The impacts of climate change on river flow regimes at the global scale. *Journal of Hydrology*, **486**, 351-364.
- Arnell, N.W., D.P. van Vuuren, and M. Isaac, 2011: The implications of climate policy for the impacts of climate change on global water resources. *Global Environmental Change: Human and Policy Dimensions*, **21**(2), 592-603.
- Arnell, N.W., J.A. Lowe, S. Brown, S.N. Gosling, P. Gottschalk, J. Hinkel, B. Lloyd-Hughes, R.J. Nicholls, T.J. Osborn, T.M. Osborne, G.A. Rose, P. Smith, and R.F. Warren, 2013: A global assessment of the effects of climate policy on the impacts of climate change. *Nature Climate Change*, **3**(5), 512-519.
- Auld, H., D. MacIver, and J. Klaassen, 2004: Heavy rainfall and waterborne disease outbreaks: the Walkerton example. *Journal of Toxicology and Environmental Health, Part A: Current Issues*, **67**(20-22), 1879-1887.
- Badjeck, M., E.H. Allison, A.S. Halls, and N.K. Dulvy, 2010: Impacts of climate variability and change on fishery-based livelihoods. *Marine Policy*, **34**(3), 375-383.
- Bae, D., I. Jung, and D.P. Lettenmaier, 2011: Hydrologic uncertainties in climate change from IPCC AR4 GCM simulations of the Chungju basin, Korea. *Journal of Hydrology*, **401**(1-2), 90-105.
- Bahri, A., 2009: *Managing the Other Side of the Water Cycle: Making Wastewater an Asset*. Global Water Partnership Technical Committee (TEC) Background Paper No.13, Global Water Partnership (GWP) Secretariat, Stockholm, Sweden, 62 pp.
- Baraer, M., B.G. Mark, J.M. McKenzie, T. Condom, J. Bury, K. Huh, C. Portocarrero, J. Gomez, and S. Rathay, 2012: Glacier recession and water resources in Peru's Cordillera Blanca. *Journal of Glaciology*, **58**(207), 134-150.
- Barnett, J. and W.N. Adger, 2007: Climate change, human security and violent conflict. *Political Geography*, **26**(6), 639-655.
- Barredo, J.I., 2009: Normalised flood losses in Europe: 1970-2006. *Natural Hazards and Earth System Sciences*, **9**(1), 97-104.
- Barrios, J.E., J.A. Rodríguez-Pineda, and M.D. Benignos, 2009: Integrated river basin management in the Conchos River basin, Mexico: a case study of freshwater climate change adaptation. *Climate and Development*, **1**(3), 249-260.
- Barthel, R., S. Janisch, D. Nickel, A. Trifkovic, and T. Hoerhan, 2010: Using the multi-actor-approach in Głowa-Danube to simulate decisions for the water supply sector under conditions of global climate change. *Water Resources Management*, **24**(2), 239-275.
- Bates, B.C., Z.W. Kundzewicz, S. Wu, and J.P. Palutikof (eds.), 2008: *Climate Change and Water*. Intergovernmental Panel on Climate Change (IPCC) Technical Paper VI, IPCC Secretariat, Geneva, Switzerland, 210 pp.
- Beniston, M., 2012: Impacts of climatic change on water and associated economic activities in the Swiss Alps. *Journal of Hydrology*, **412**, 291-296.
- Benítez-Gilbert, M., M. Alvarez-Cobelas, and D.G. Angeler, 2010: Effects of climatic change on stream water quality in Spain. *Climatic Change*, **103**(3), 339-352.
- Benito, G. and M.J. Machado, 2012: Floods in the Iberian Peninsula. In: *Changes in Flood Risk in Europe* [Kundzewicz, Z.W. (ed.)]. CRC Press, Wallingford, UK, pp. 372-383.
- Berg, P., C. Moseley, and J.O. Haerter, 2013: Strong increase in convective precipitation in response to higher temperatures. *Nature Geoscience*, **6**(3), 181-185.
- Bergsma, E., J. Gupta, and P. Jong, 2012: Does individual responsibility increase the adaptive capacity of society? The case of local water management in the Netherlands. *Resources Conservation and Recycling*, **64**, 13-22.
- Beyene, T., D.P. Lettenmaier, and P. Kabat, 2010: Hydrologic impacts of climate change on the Nile River basin: implications of the 2007 IPCC scenarios. *Climatic Change*, **100**(3-4), 433-461.
- Bhutiyani, M.R., V.S. Kale, and N.J. Pawar, 2008: Changing streamflow patterns in the rivers of northwestern Himalaya: implications of global warming in the 20th century. *Current Science*, **95**(5), 618-626.
- Biemans, H., L. Speelman, F. Ludwig, E. Moors, A.J. Wiltshire, P. Kumar, D. Gerten, and P. Kabat, 2013: Future water resources for food production in five South Asian river basins and potential of adaptation options – a modeling study. *Science of the Total Environment* (in press), doi:10.1016/j.scitotenv.2013.05.092.
- Black, M. and J. King, 2009: *The Atlas of Water: Mapping the World's Most Critical Resource*. 2nd edn., University of California Press, Berkeley, CA, USA, 128 pp.
- Blöschl, G. and A. Montanari, 2010: Climate change impacts-throwing the dice? *Hydrological Processes*, **24**(3), 374-381.
- Bolch, T., A. Kulkarni, A. Kaab, C. Huggel, F. Paul, J.G. Cogley, H. Frey, J.S. Kargel, K. Fujita, M. Scheel, S. Bajracharya, and M. Stoffel, 2012: The state and fate of Himalayan glaciers. *Science*, **336**(6079), 310-314.
- Bonte, M. and J.J.G. Zwolsman, 2010: Climate change induced salinisation of artificial lakes in the Netherlands and consequences for drinking water production. *Water Research*, **44**(15), 4411-4424.
- Bourne, C.M., D.G. Kehler, Y.F. Wiersma, and D. Cote, 2011: Barriers to fish passage and barriers to fish passage assessments: the impact of assessment methods and assumptions on barrier identification and quantification of watershed connectivity. *Aquatic Ecology*, **45**(3), 389-403.
- Bouwer, L.M., 2011: Have disaster losses increased due to anthropogenic climate change? *Bulletin of the American Meteorological Society*, **92**(1), 39-46.
- Bouwer, L.M., 2013: Projections of future extreme weather losses under changes in climate and exposure. *Risk Analysis*, **33**(5), 915-930.
- Bowes, M.J., E. Gozzard, A.C. Johnson, P.M. Scarlett, C. Roberts, D.S. Read, L.K. Armstrong, S.A. Harman, and H.D. Wickham, 2012: Spatial and temporal changes in chlorophyll-a concentrations in the River Thames basin, UK: are phosphorus concentrations beginning to limit phytoplankton biomass? *Science of the Total Environment*, **426**, 45-55.

- Boxall**, A.B.A., A. Hardy, S. Beulke, T. Boucard, L. Burgin, P.D. Falloon, P.M. Haygarth, T. Hutchinson, R.S. Kovats, G. Leonardi, L.S. Levy, G. Nichols, S.A. Parsons, L. Potts, D. Stone, E. Topp, D.B. Turley, K. Walsh, E.M.H. Wellington, and R.J. Williams, 2009: Impacts of climate change on indirect human exposure to pathogens and chemicals from agriculture. *Environmental Health Perspectives*, **117**(4), 508-514.
- Brauman**, K.A., S. Siebert, and J.A. Foley, 2013: Improvements in crop water productivity increase water sustainability and food security—a global analysis. *Environmental Research Letters*, **8**(2), 024030, doi:10.1088/1748-9326/8/2/024030.
- Brekke**, L.D., M.D. Dettinger, E.P. Maurer, and M. Anderson, 2008: Significance of model credibility in estimating climate projection distributions for regional hydroclimatological risk assessments. *Climatic Change*, **89**(3-4), 371-394.
- Brekke**, L.D., J.E. Kiang, J.R. Olsen, R.S. Pulwarty, D.A. Raff, D.P. Turnipseed, R.S. Webb, and K.D. White, 2009a: *Climate Change and Water Resources Management – A Federal Perspective*. USGS Circular 133, U.S. Geological Survey (USGS), Reston, VA, USA, 65 pp.
- Brekke**, L.D., E.P. Maurer, J.D. Anderson, M.D. Dettinger, E.S. Townsley, A. Harrison, and T. Pruitt, 2009b: Assessing reservoir operations risk under climate change. *Water Resources Research*, **45**, W04411, doi:10.1029/2008WR00694.
- Brikowski**, T.H., 2008: Doomed reservoirs in Kansas, USA? Climate change and groundwater mining on the Great Plains lead to unsustainable surface water storage. *Journal of Hydrology*, **354**(1-4), 90-101.
- Brooks**, J.P., A. Adeli, J.J. Read, and M.R. McLaughlin, 2009: Rainfall simulation in greenhouse microcosms to assess bacterial-associated runoff from land-applied poultry litter. *Journal of Environmental Quality*, **38**(1), 218-229.
- Browning-Aiken**, A., B. Morehouse, A. Davis, M. Wilder, R. Varady, D. Goodrich, R. Carter, D. Moreno, and E.D. McGovern, 2007: Climate, water management, and policy in the San Pedro basin: results of a survey of Mexican stakeholders near the U.S.-Mexico border. *Climatic Change*, **85**(3-4), 323-341.
- Bruno**, M.C., B. Maiolini, M. Carulli, and L. Silveri, 2009: Impact of hydropeaking on hyporheic invertebrates in an Alpine stream (Trentino, Italy). *Annales De Limnologie – International Journal of Limnology*, **45**(3), 157-170.
- Buhaug**, H., N.P. Gleditsch, and O.M. Theisen, 2010: Implications of climate change for armed conflict. In: *Social Dimensions of Climate Change: Equity and Vulnerability in a Warming World* [Mearns, R. and A. Norton (eds.)]. The World Bank, Washington DC, USA, pp. 75-102.
- Burke**, M.B., E. Miguel, S. Satyanath, J.A. Dykema, and D.B. Lobell, 2009: Warming increases the risk of civil war in Africa. *Proceedings of the National Academy of Sciences of the United States of America*, **106**(49), 20670-20674.
- Burn**, D.H., M. Sharif, and K. Zhang, 2010: Detection of trends in hydrological extremes for Canadian watersheds. *Hydrological Processes*, **24**(13), 1781-1790.
- Burton**, I., 2008: Climate change and the adaptation deficit. In: *The Earthscan Reader on Adaptation to Climate Change* [Lisa, E., F. Schipper, and I. Burton (eds.)]. Routledge, London, UK, pp. 89-95.
- Bussi**, G., X. Rodríguez-Lloveras, F. Francés, G. Benito, Y. Sánchez-Moya, and A. Sopena, 2013: Sediment yield model implementation based on check dam infill stratigraphy in a semiarid Mediterranean catchment. *Hydrology and Earth System Sciences*, **17**, 3339-3354.
- Butscher**, C. and P. Huguenberger, 2009: Modeling the temporal variability of karst groundwater vulnerability, with implications for climate change. *Environmental Science and Technology*, **43**(6), 1665-1669.
- Campbell**, A., A. Chenery, L. Coad, V. Kapos, F. Kershaw, J. Scharlemann, and B. Dickson, 2008: *The Linkages between Biodiversity and Climate Change Mitigation: A Review of the Recent Scientific Literature*. United Nations Environment Programme World Conservation Monitoring Centre, Cambridge, UK, 61 pp.
- Carneiro**, J.F., M. Boughriba, A. Correia, Y. Zarhloule, A. Rimi, and B. El Houadi, 2010: Evaluation of climate change effects in a coastal aquifer in Morocco using a density-dependent numerical model. *Environmental Earth Sciences*, **61**(2), 241-252.
- Cayan**, D.R., S.A. Kammerdiener, M.D. Dettinger, J.M. Caprio, and D.H. Peterson, 2001: Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society*, **82**(3), 399-415.
- Chakraborti**, D., B. Das, and M.T. Murrill, 2011: Examining India's groundwater quality management. *Environmental Science and Technology*, **45**(1), 27-33.
- Chang**, H., 2004: Water quality impacts of climate and land use changes in southeastern Pennsylvania. *Professional Geographer*, **56**(2), 240-257.
- Chang**, H., J. Franczyk, and C. Kim, 2009: What is responsible for increasing flood risks? The case of Gangwon Province, Korea. *Natural Hazards*, **48**(3), 339-354.
- Changnon**, S.A., 1969: Recent studies of urban effects on precipitation in the United States. *Bulletin of the American Meteorological Society*, **50**(6), 411-421.
- Chen**, C., J.O. Haerter, S. Hagemann, and C. Piani, 2011: On the contribution of statistical bias correction to the uncertainty in the projected hydrological cycle. *Geophysical Research Letters*, **38**(20), L20403, doi:10.1029/2011GL049318.
- Chen**, G., H. Tian, C. Zhang, M. Liu, W. Ren, W. Zhu, A.H. Chappelka, S.A. Prior, and G.B. Lockaby, 2012: Drought in the Southern United States over the 20th century: variability and its impacts on terrestrial ecosystem productivity and carbon storage. *Climatic Change*, **114**(2), 379-397.
- Chen**, J., F.P. Brissette, and R. Leconte, 2011: Uncertainty of downscaling method in quantifying the impact of climate change on hydrology. *Journal of Hydrology*, **401**(3-4), 190-202.
- Chiew**, F.H.S., J. Teng, J. Vaze, D.A. Post, J.M. Perraud, D.G.C. Kirono, and N.R. Viney, 2009: Estimating climate change impact on runoff across southeast Australia: method, results, and implications of the modeling method. *Water Resources Research*, **45**(10), W10414, doi:10.1029/2008WR007338.
- Chisholm**, R.A., 2010: Trade-offs between ecosystem services: water and carbon in a biodiversity hotspot. *Ecological Economics*, **69**(10), 1973-1987.
- Christerson**, B.V., J. Vidal, and S.D. Wade, 2012: Using UKCP09 probabilistic climate information for UK water resource planning. *Journal of Hydrology*, **424**, 48-67.
- Cloke**, H.L., C. Jeffers, F. Wetterhall, T. Byrne, J. Lowe, and F. Pappenberger, 2010: Climate impacts on river flow: projections for the Medway catchment, UK, with UKCP09 and CATCHMOD. *Hydrological Processes*, **24**(24), 3476-3489.
- Clow**, D.W., 2010: Changes in the timing of snowmelt and streamflow in Colorado: a response to recent warming. *Journal of Climate*, **23**(9), 2293-2306.
- Collins**, D.N., 2008: Climatic warming, glacier recession and runoff from Alpine basins after the Little Ice Age maximum. *Annals of Glaciology*, **48**(1), 119-124.
- Connell-Buck**, C.R., J. Medellin-Azuara, J.R. Lund, and K. Madani, 2011: Adapting California's water system to warm vs. dry climates. *Climatic Change*, **109**, 133-149.
- Conway**, D., A. Persechino, S. Ardoin-Bardin, H. Hamandawana, C. Dieulin, and G. Mahe, 2009: Rainfall and water resources variability in Sub-Saharan Africa during the twentieth century. *Journal of Hydrometeorology*, **10**(1), 41-59.
- Cooley**, H., 2008: Water management in a changing climate. In: *The World's Water 2008-2009: The Biennial Report on Freshwater Resources* [Gleick, P.H. (ed.)]. Island Press, Washington DC, USA, pp. 39-56.
- Couwenberg**, J., R. Dommain, and H. Joosten, 2010: Greenhouse gas fluxes from tropical peatlands in south-east Asia. *Global Change Biology*, **16**(6), 1715-1732.
- Crosbie**, R.S., T. Pickett, F.S. Mpelasoka, G. Hodgson, S.P. Charles, and O.V. Barron, 2013a: An assessment of the climate change impacts on groundwater recharge at a continental scale using a probabilistic approach with an ensemble of GCMs. *Climatic Change*, **117**(1-2), 41-53.
- Crosbie**, R.S., B.R. Scanlon, F.S. Mpelasoka, R.C. Reedy, J.B. Gates, and L. Zhang, 2013b: Potential climate change effects on groundwater recharge in the High Plains Aquifer, USA. *Water Resources Research*, **49**(7), 3936-3951.
- Cruz**, R.V., H. Harasawa, M. Lal, S. Wu, Y. Anokhin, B. Punsalmaa, Y. Honda, M. Jafari, C. Li, and N. Huu Ninh, 2007: Asia. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 469-506.
- Cunderlik**, J.M. and T.B.M.J. Ouarda, 2009: Trends in the timing and magnitude of floods in Canada. *Journal of Hydrology*, **375**(3-4), 471-480.
- Cunderlik**, J.M. and S.P. Simonovic, 2007: Inverse flood risk modelling under changing climatic conditions. *Hydrological Processes*, **21**(5), 563-577.
- Curriero**, F., J. Patz, J. Rose, and S. Lele, 2001: The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948-1994. *American Journal of Public Health*, **91**(8), 1194-1199.
- Dahlke**, H.E., S.W. Lyon, J.R. Stedinger, G. Rosqvist, and P. Jansson, 2012: Contrasting trends in floods for two sub-arctic catchments in northern Sweden—does glacier presence matter? *Hydrology and Earth System Sciences*, **16**(7), 2123-2141.
- Dai**, A., 2013: Increasing drought under global warming in observations and models. *Nature Climate Change*, **3**, 52-58.
- Dai**, A., T. Qian, K.E. Trenberth, and J.D. Milliman, 2009: Changes in continental freshwater discharge from 1948 to 2004. *Journal of Climate*, **22**(10), 2773-2792.
- Dai**, S.B., X.X. Lu, S.L. Yang, and A.M. Cai, 2008: A preliminary estimate of human and natural contributions to the decline in sediment flux from the Yangtze River to the East China Sea. *Quaternary International*, **186**(1), 43-54.

- Dankers, R., N.W. Arnell, D.B. Clark, P. Falloon, B.M. Fekete, S.N. Gosling, J. Heinke, H. Kim, Y. Masaki, Y. Satoh, and T. Stacke, 2013:** First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. *Proceedings of the National Academy of Sciences of the United States of America* (in press), doi:10.1073/pnas.1302078110.
- de Graaf, R. and R.V. der Brugge, 2010:** Transforming water infrastructure by linking water management and urban renewal in Rotterdam. *Technological Forecasting and Social Change, 77(8)*, 1282-1291.
- Dembo, R., 2010:** Why refitting buildings is key to reducing emission. *Urban World 1(5)*, 34-37.
- de Rham, L.P., T.D. Prowse, and B.R. Bonsal, 2008:** Temporal variations in river-ice break-up over the Mackenzie River basin, Canada. *Journal of Hydrology, 349(3-4)*, 441-454.
- Dessai, S., M. Hulme, R. Lempert, and R. Pielke, 2009:** Climate prediction: a limit to adaptation? In: *Adapting to Climate Change: Thresholds, Values, Governance* [Adger, W.N., I. Lorenzoni, and K.L. O'Brien (eds.)]. Cambridge University Press, Cambridge, UK, pp. 64-78.
- Dillon, P.J. and B. Jiménez, 2008:** Water reuse via aquifer recharge: intentional and unintentional practices. In: *Water Reuse: An International Survey of Current Practice, Issues and Needs* [Jiménez, B. and T. Asano (eds.)]. IWA Publishing, London, UK, pp. 260-280.
- Döll, P., 2009:** Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. *Environmental Research Letters, 4(3)*, 035006, doi:10.1088/1748-9326/4/3/035006.
- Döll, P. and H. Müller Schmied, 2012:** How is the impact of climate change on river flow regimes related to the impact on mean annual runoff? A global-scale analysis. *Environmental Research Letters, 7*, 014037, doi:10.1088/1748-9326/7/1/014037.
- Döll, P. and J. Zhang, 2010:** Impact of climate change on freshwater ecosystems: a global-scale analysis of ecologically relevant river flow alterations. *Hydrology and Earth System Sciences, 14(5)*, 783-799.
- Donohue, R.J., M.L. Roderick, and T.R. McVicar, 2011:** Assessing the differences in sensitivities of runoff to changes in climatic conditions across a large basin. *Journal of Hydrology, 406(3-4)*, 234-244.
- Ducharme, A., 2008:** Importance of stream temperature to climate change impact on water quality. *Hydrology and Earth System Sciences, 12(3)*, 797-810.
- Earman, S., A.R. Campbell, F.M. Phillips, and B.D. Newman, 2006:** Isotopic exchange between snow and atmospheric water vapor: estimation of the snowmelt component of groundwater recharge in the southwestern United States. *Journal of Geophysical Research: Atmospheres, 111(D9)*, D09302, doi:10.1029/2005JD006470.
- Elliott, M., A. Armstrong, J. Lobuglio, and J. Bartram, 2011:** *Technologies for Climate Change Adaptation: The Water Sector* [De Lopez, T. (ed.)]. TNA Guidebook Series, UNEP Risk Centre, Roskilde, Denmark, 114 pp.
- Emelko, M.B., U. Silins, K.D. Bladon, and M. Stone, 2011:** Implications of land disturbance on drinking water treatability in a changing climate: demonstrating the need for "source water supply and protection" strategies. *Water Research, 45(2)*, 461-472.
- Engle, N.L. and M.C. Lemos, 2010:** Unpacking governance: Building adaptive capacity to climate change of river basins in Brazil. *Global Environmental Change: Human and Policy Dimensions, 20(1)*, 4-13.
- European Communities, 2009:** *Guidance Document No. 24: River Basin Management in a Changing Climate*. Common Implementation Strategy for the Water Framework Directive (2000/60/EC), Technical Report-2009-040, European Communities, Luxembourg, Luxembourg, 134 pp.
- Evans, C.D., D.T. Monteith, and D.M. Cooper, 2005:** Long-term increases in surface water dissolved organic carbon: observations, possible causes and environmental impacts. *Environmental Pollution, 137(1)*, 55-71.
- Falloon, P.D. and R.A. Betts, 2006:** The impact of climate change on global river flow in HadGEM1 simulations. *Atmospheric Science Letters, 7(3)*, 62-68.
- Falloon, P.D. and R.A. Betts, 2010:** Climate impacts on European agriculture and water management in the context of adaptation and mitigation – the importance of an integrated approach. *Science of the Total Environment, 408(23)*, 5667-5687.
- Falloon, P., R. Betts, A. Wiltshire, R. Dankers, C. Mathison, D. McNeill, P. Bates, and M. Trigg, 2011:** Validation of river flows in HadGEM1 and HadCM3 with the TRIP river flow model. *Journal of Hydrometeorology, 12(6)*, 1157-1180.
- Favis-Mortlock, D. and J. Boardman, 1995:** Nonlinear responses of soil-erosion to climate-change – a modeling study on the UK south-downs. *Catena, 25(1-4)*, 365-387.
- Ferguson, G. and T. Gleeson, 2012:** Vulnerability of coastal aquifers to groundwater use and climate change. *Nature Climate Change, 2*, 342-345.
- Ferguson, I.M. and R.M. Maxwell, 2010:** Role of groundwater in watershed response and land surface feedbacks under climate change. *Water Resources Research, 46*, W00F02, doi:10.1029/2009WR008616.
- Fernandez, R.A., J.B. Anderson, J.S. Wellner, and B. Hallet, 2011:** Timescale dependence of glacial erosion rates: a case study of Marinelli Glacier, Cordillera Darwin, southern Patagonia. *Journal of Geophysical Research: Earth Surface, 116(1)*, F01020, doi:10.1029/2010JF001685.
- Feyen, L., R. Dankers, K. Bodis, P. Salamon, and J.I. Barredo, 2012:** Fluvial flood risk in Europe in present and future climates. *Climatic Change, 112(1)*, 47-62.
- Ficke, A.D., C.A. Myrick, and L.J. Hansen, 2007:** Potential impacts of global climate change on freshwater fisheries. *Reviews in Fish Biology and Fisheries, 17(4)*, 581-613.
- Finger, R., W. Hediger, and S. Schmid, 2011:** Irrigation as adaptation strategy to climate change – a biophysical and economic appraisal for Swiss maize production. *Climatic Change, 105(3-4)*, 509-528.
- Fischer, T., M. Gemmer, L. Liu, and B. Su, 2011:** Temperature and precipitation trends and dryness/wetness pattern in the Zhujiang River basin, south China, 1961-2007. *Quaternary International, 244(2)*, 138-148.
- Fischer, T., C. Menz, B. Su, and T. Scholten, 2013:** Simulated and projected climate extremes in the Zhujiang River basin, south China, using the regional climate model COSMO-CLM. *International Journal of Climatology, 33*, 2988-3001.
- Flörke, M., I. Baerlund, and E. Kynast, 2012:** Will climate change affect the electricity production sector? A European study. *Journal of Water and Climate Change, 3(1)*, 44-54.
- Fowler, H.J. and C.G. Kilsby, 2007:** Using regional climate model data to simulate historical and future river flows in northwest England. *Climatic Change, 80(3-4)*, 337-367.
- Fowler, H.J., S. Blenkinsop, and C. Tebaldi, 2007:** Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. *International Journal of Climatology, 27(12)*, 1547-1578.
- Freas, K., B. Bailey, A. Munevar, and S. Butler, 2008:** Incorporating climate change in water planning. *Journal American Water Works Association, 100(6)*, 92-99.
- Fu, G., S.P. Charles, and J. Yu, 2009:** A critical overview of pan evaporation trends over the last 50 years. *Climatic Change, 97(1-2)*, 193-214.
- Fu, G., S.P. Charles, F.H.S. Chiew, J. Teng, H. Zheng, A.J. Frost, W. Liu, and S. Kirshner, 2013:** Modelling runoff with statistically downscaled daily site, gridded and catchment rainfall series. *Journal of Hydrology, 492*, 254-265.
- Fujihara, Y., K. Tanaka, T. Watanabe, T. Nagano, and T. Kojiri, 2008a:** Assessing the impacts of climate change on the water resources of the Seyhan River basin in Turkey: use of dynamically downscaled data for hydrologic simulations. *Journal of Hydrology, 353(1-2)*, 33-48.
- Fujihara, Y., S.P. Simonovic, F. Topaloglu, K. Tanaka, and T. Watanabe, 2008b:** An inverse-modelling approach to assess the impacts of climate change in the Seyhan River basin, Turkey. *Hydrological Sciences Journal, 53(6)*, 1121-1136.
- Fujita, K., A. Sakai, S. Takenaka, T. Nuimura, A.B. Surazakov, T. Sawagaki, and T. Yamanokuchi, 2013:** Potential flood volume of Himalayan glacial lakes. *Natural Hazards and Earth System Sciences, 13(7)*, 1827-1839.
- Fung, F., A. Lopez, and M. New, 2011:** Water availability in +2 degrees C and +4 degrees C worlds. *Philosophical Transactions of the Royal Society A, 369(1934)*, 99-116.
- Gardelle, J., Y. Arnaud, and E. Berthier, 2011:** Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. *Global and Planetary Change, 75(1-2)*, 47-55.
- Gardner, A.S., G. Moholdt, J.G. Cogley, B. Wouters, A.A. Arendt, J. Wahr, E. Berthier, R. Hock, W.T. Pfeffer, G. Kaser, S.R.M. Ligtenberg, T. Bolch, M.J. Sharp, J.O. Hagen, M.R. van den Broeke, and F. Paul, 2013:** A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science, 340(6134)*, 852-857.
- Gascuel-Odoux, C., P. Arousseau, P. Durand, L. Ruiz, and J. Molenat, 2010:** The role of climate on inter-annual variation in stream nitrate fluxes and concentrations. *Science of the Total Environment, 408(23)*, 5657-5666.
- Gemmer, M., T. Fischer, T. Jiang, B. Su, and L.L. Liu, 2011:** Trends in precipitation extremes in the Zhujiang River basin, South China. *Journal of Climate, 24(3)*, 750-761.
- Gerbens-Leenes, P.W., A.R. van Lienden, A.Y. Hoekstra, and T.H. van der Meer, 2012:** Biofuel scenarios in a water perspective: the global blue and green water footprint of road transport in 2030. *Global Environmental Change: Human and Policy Dimensions, 22(3)*, 764-775.

- Gersonius, B., R. Ashley, A. Pathirana, and C. Zevenbergen, 2013:** Climate change uncertainty: building flexibility into water and flood risk infrastructure. *Climatic Change*, **116(2)**, 411-423.
- Gerten, D., S. Rost, W. von Bloh, and W. Lucht, 2008:** Causes of change in 20th century global river discharge. *Geophysical Research Letters*, **35(20)**, L20405, doi:10.1029/2008GL035258.
- Gerten, D., J. Heinke, H. Hoff, H. Biemans, M. Fader, and K. Waha, 2011:** Global water availability and requirements for future food production. *Journal of Hydrometeorology*, **12(5)**, 885-899.
- Gerten, D., W. Lucht, S. Ostberg, J. Heinke, M. Kowarsch, H. Kreft, Z.W. Kundzewicz, J. Rastgooy, R. Warren, and H.J. Schellnhuber, 2013:** Asynchronous exposure to global warming: freshwater resources and terrestrial ecosystems. *Environmental Research Letters*, **8(3)**, 034032, doi:10.1088/1748-9326/8/3/034032.
- Giuntoli, I., B. Renard, and M. Lang, 2012:** Floods in France. In: *Changes in Flood Risk in Europe* [Kundzewicz, Z.W. (ed.)]. CRC Press, Wallingford, UK, pp. 199-211.
- Goderniaux, P., S. Brouyere, S. Blenkinsop, A. Burton, H.J. Fowler, P. Orban, and A. Dassargues, 2011:** Modeling climate change impacts on groundwater resources using transient stochastic climatic scenarios. *Water Resources Research*, **47(12)**, W12516, doi:10.1029/2010WR010082.
- Godfrey, S., P. Labhasetwar, S. Wate, and B. Jimenez, 2010:** Safe greywater reuse to augment water supply and provide sanitation in semi-arid areas of rural India. *Water Science and Technology*, **62(6)**, 1296-1303.
- Golombek, R., S.A.C. Kittelsen, and I. Haddeland, 2012:** Climate change: impacts on electricity markets in Western Europe. *Climatic Change*, **113(2)**, 357-370.
- Gosling, S.N. and N.W. Arnell, 2013:** A global assessment of the impact of climate change on water scarcity. *Climatic Change*, 15 pp. (in press), doi:10.1007/s10584-013-0853-x.
- Gosling, S.N., D. Bretherton, K. Haines, and N.W. Arnell, 2010:** Global hydrology modelling and uncertainty: running multiple ensembles with a campus grid. *Philosophical Transactions of the Royal Society A*, **368(1926)**, 4005-4021.
- Goulden, M., D. Conway, and A. Persechino, 2009:** Adaptation to climate change in international river basins in Africa: a review. *Hydrological Sciences Journal*, **54(5)**, 805-828.
- Green, T.R., M. Taniguchi, H. Kooi, J.J. Gurdak, D.M. Allen, K.M. Hiscock, H. Treidel, and A. Aureli, 2011:** Beneath the surface of global change: impacts of climate change on groundwater. *Journal of Hydrology*, **405(3-4)**, 532-560.
- Griffiths-Sattenspiel, B. and W. Wilson, 2009:** *The Carbon Footprint of Water*. A River Network Report, River Network, Portland, OR, USA, 49 pp.
- Grosse, G., V. Romanovsky, T. Jorgenson, K.W. Anthony, J. Brown, and P.P. Overduin, 2011:** Vulnerability and feedbacks of permafrost to climate change. *Eos, Transactions American Geophysical Union*, **92(9)**, 73-74.
- Gujja, B., S. Dalai, H. Shaik, and V. Goud, 2009:** Adapting to climate change in the Godavari River basin of India by restoring traditional water storage systems. *Climate and Development*, **1(3)**, 229-240.
- Gunkel, G., 2009:** Hydropower – a green energy? Tropical reservoirs and greenhouse gas emissions. *Clean – Soil, Air, Water*, **37(9)**, 726-734.
- Gupta, A., K.V. Bharadwaj, S. Lama, and J. Mathur, 2010:** Energy analysis of irrigated jetropha cultivation for producing biodiesel. *Low Carbon Economy*, **1**, 54-60.
- Hagemann, S., C. Chen, J.O. Haerter, J. Heinke, D. Gerten, and C. Piani, 2011:** Impact of a statistical bias correction on the projected hydrological changes obtained from three GCMs and two hydrology models. *Journal of Hydrometeorology*, **12(4)**, 556-578.
- Hagemann, S., C. Chen, D.B. Clark, S. Folwell, S.N. Gosling, I. Haddeland, N. Hanasaki, J. Heinke, F. Ludwig, F. Voß, and A.J. Wiltshire, 2013:** Climate change impact on available water resources obtained using multiple global climate and hydrology models. *Earth System Dynamics*, **4**, 129-144.
- Hall, J., 2007:** Probabilistic climate scenarios may misrepresent uncertainty and lead to bad adaptation decisions. *Hydrological Processes*, **21(8)**, 1127-1129.
- Hall, J. and C. Murphy, 2010:** Vulnerability analysis of future public water supply under changing climate conditions: a study of the Moy Catchment, western Ireland. *Water Resources Management*, **24(13)**, 3527-3545.
- Hall, J.W., G. Watts, M. Keil, L. de Vial, R. Street, K. Conlan, P.E. O'Connell, K.J. Beven, and C.G. Kilsby, 2012:** Towards risk-based water resources planning in England and Wales under a changing climate. *Water and Environment Journal*, **26(1)**, 118-129.
- Hamin, E.M. and N. Gurran, 2009:** Urban form and climate change: balancing adaptation and mitigation in the US and Australia. *Habitat International*, **33(3)**, 238-245.
- Hanasaki, N., S. Fujimori, T. Yamamoto, S. Yoshikawa, Y. Masaki, Y. Hijioka, M. Kainuma, Y. Kanamori, T. Masui, K. Takahashi, and S. Kanae, 2013:** A global water scarcity assessment under Shared Socio-economic Pathways – part 2: water availability and scarcity. *Hydrology and Earth System Sciences*, **17**, 2393-2413.
- Handmer, J., Y. Honda, Z.W. Kundzewicz, N. Arnell, G. Benito, J. Hatfield, I.F. Mohamed, P. Peduzzi, S. Wu, B. Sherstyukov, K. Takahashi, and Z. Yan, 2012:** Changes in impacts of climate extremes: human systems and ecosystems. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, USA, pp. 231-290.
- Hannaford, J. and J.W. Hall, 2012:** Flood risk in the UK: evidence of change and management responses. In: *Changes in Flood Risk in Europe* [Kundzewicz, Z.W. (ed.)]. CRC Press, Wallingford, UK, pp. 344-361.
- Harris, C., L.U. Arenson, H.H. Christiansen, B. Etzelmüller, R. Frauenfelder, S. Gruber, W. Haeblerli, C. Hauck, M. Hoelzle, O. Humlum, K. Isaksen, A. Kääh, M.A. Kern-Lütschg, M. Lehning, N. Matsuoka, J.B. Murton, J. Noezli, M. Phillips, N. Ross, M. Seppälä, S.M. Springman, and D.V. Mühll, 2009:** Permafrost and climate in Europe: monitoring and modelling thermal, geomorphological and geotechnical responses. *Earth-Science Reviews*, **92(3-4)**, 117-171.
- Hattermann, F.F., Z.W. Kundzewicz, S. Huang, T. Vetter, W. Kron, O. Burghoff, B. Merz, A. Bronstert, V. Krysanova, F.-W. Gerstengarbe, P. Werner, and Y. Hauf, 2012:** Flood risk from a holistic perspective – observed changes in Germany. In: *Changes in Flood Risk in Europe* [Kundzewicz, Z.W. (ed.)]. CRC Press, Wallingford, UK, pp. 212-237.
- Hawkins, E. and R. Sutton, 2011:** The potential to narrow uncertainty in projections of regional precipitation change. *Climate Dynamics*, **37(1-2)**, 407-418.
- Hayashi, A., K. Akimoto, F. Sano, S. Mori, and T. Tomoda, 2010:** Evaluation of global warming impacts for different levels of stabilization as a step toward determination of the long-term stabilization target. *Climatic Change*, **98**, 87-112.
- Henderson, J., C. Rodgers, R. Jones, J. Smith, K. Strzepek, J. Martinich, 2013:** Economic impacts of climate change on water resources in the coterminous United States. *Mitigation and Adaptation Strategies for Global Change*, 23 pp. (in press), doi:10.1007/s11027-013-9483-x.
- Henriques, C. and G. Spraggs, 2011:** Alleviating the flood risk of critical water supply sites: asset and system resilience. *Journal of Water Supply Research and Technology – Aqua*, **60(1)**, 61-68.
- Hidalgo, H.G., T. Das, M.D. Dettinger, D.R. Cayan, D.W. Pierce, T.P. Barnett, G. Bala, A. Mirin, A.W. Wood, C. Bonfils, B.D. Santer, and T. Nozawa, 2009:** Detection and attribution of streamflow timing changes to climate change in the western United States. *Journal of Climate*, **22(13)**, 3838-3855.
- Hilker, N., A. Badoux, and C. Hegg, 2009:** The Swiss flood and landslide damage database 1972-2007. *Natural Hazards and Earth System Sciences*, **9(3)**, 913-925.
- Hirabayashi, Y., S. Kanae, S. Emori, T. Oki, and M. Kimoto, 2008:** Global projections of changing risks of floods and droughts in a changing climate. *Hydrological Sciences Journal*, **53(4)**, 754-772.
- Hirabayashi, Y., R. Mahendran, S. Koirala, L. Konoshima, D. Yamazaki, S. Watanabe, and S. Kanae, 2013:** Global flood risk under climate change. *Nature Climate Change*, **3**, 816-821.
- Hirsch, R.M. and K.R. Ryberg, 2012:** Has the magnitude of floods across the USA changed with global CO₂ levels? *Hydrological Sciences Journal*, **57(1)**, 1-9.
- Hirschi, M., S.I. Seneviratne, V. Alexandrov, F. Boberg, C. Boroneant, O.B. Christensen, H. Formayer, B. Orlowsky, and P. Stepanek, 2011:** Observational evidence for soil-moisture impact on hot extremes in southeastern Europe. *Nature Geoscience*, **4(1)**, 17-21.
- Hoekstra, A.Y. and J. de Kok, 2008:** Adapting to climate change: a comparison of two strategies for dike heightening. *Natural Hazards*, **47(2)**, 217-228.
- Holman, I.P., D. Tascone, and T.M. Hess, 2009:** A comparison of stochastic and deterministic downscaling methods for modelling potential groundwater recharge under climate change in East Anglia, UK: implications for groundwater resource management. *Hydrogeology Journal*, **17(7)**, 1629-1641.
- Hooijer, A., S. Page, J.G. Canadell, M. Silvius, J. Kwadijk, H. Wösten, and J. Jauhainen, 2010:** Current and future CO₂ emissions from drained peatlands in Southeast Asia. *Biogeosciences*, **7(5)**, 1505-1514.
- House, J.I., H.G. Orr, J.M. Clark, A.V. Gallego-Sala, C. Freeman, I.C. Prentice, and P. Smith, 2010:** Climate change and the British Uplands: evidence for decision-making. *Climate Research*, **45(1)**, 3-12.

- Howard, G., K. Charles, K. Pond, A. Brookshaw, R. Hossain, and J. Bartram, 2010: Securing 2020 vision for 2030: climate change and ensuring resilience in water and sanitation services. *Journal of Water and Climate Change*, **1(1)**, 2-16.
- Howden, N.J.K., T.P. Burt, F. Worrall, M.J. Whelan, and M. Bierzo, 2010: Nitrate concentrations and fluxes in the River Thames over 140 years (1868-2008): are increases irreversible? *Hydrological Processes*, **24(18)**, 2657-2662.
- Hsiang, S.M., K.C. Meng, and M.A. Cane, 2011: Civil conflicts are associated with the global climate. *Nature*, **476**, 438-441.
- Huard, D., 2011: A black eye for the *Hydrological Sciences Journal*. Discussion of 'A comparison of local and aggregated climate model outputs with observed data' by G.G. Anagnostopoulos et al. (2010, *Hydrological Sciences Journal*, **55(7)**, 1094-1110). *Hydrological Sciences Journal*, **56(7)**, 1330-1333.
- Huggel, C., J.J. Clague, and O. Korup, 2012: Is climate change responsible for changing landslide activity in high mountains? *Earth Surface Processes and Landforms*, **37(1)**, 77-91.
- Hughes, D.A., D.G. Kingston, and M.C. Todd, 2011: Uncertainty in water resources availability in the Okavango River basin as a result of climate change. *Hydrology and Earth System Sciences*, **15(3)**, 931-941.
- Huntjens, P., C. Pahl-Wostl, and J. Grin, 2010: Climate change adaptation in European river basins. *Regional Environmental Change*, **10(4)**, 263-284.
- Huntjens, P., L. Lebel, C. Pahl-Wostl, J. Camkin, R. Schulze, and N. Kranz, 2012: Institutional design propositions for the governance of adaptation to climate change in the water sector. *Global Environmental Change: Human and Policy Dimensions*, **22(1)**, 67-81.
- Huss, M., 2011: Present and future contribution of glacier storage change to runoff from macroscale drainage basins in Europe. *Water Resources Research*, **47**, W07511, doi:10.1029/2010WR010299.
- Immerzeel, W.W., F. Pellicciotti, and M.F.P. Bierkens, 2013: Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. *Nature Geoscience*, **6**, 742-745.
- IPCC, 2007: *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K, and A. Reisinger (eds.)]. IPCC, Geneva, Switzerland, 104 pp.
- IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.
- Ishak, E.H., A. Rahman, S. Westra, A. Sharma, and G. Kuczera, 2010: Preliminary analysis of trends in Australian flood data. In: *World Environmental and Water Resources Congress 2010: Challenges of Change* [Palmer, R.N. (ed.)]. Proceedings of the Congress, American Society of Civil Engineers, Reston, VA, USA, pp. 115-124.
- ISO, 2009: *ISO 31000: 2009 Risk Management – Principles and Guidelines*. International Organization for Standardization (ISO), Geneva, Switzerland, 24 pp.
- Jackson, C.R., R. Meister, and C. Prudhomme, 2011: Modelling the effects of climate change and its uncertainty on UK Chalk groundwater resources from an ensemble of global climate model projections. *Journal of Hydrology*, **399(1-2)**, 12-28.
- Jackson, R.E., A.W. Gorody, B. Mayer, J.W. Roy, M.C. Ryan, and D.R. Van Stempvoort, 2013: Groundwater protection and unconventional gas extraction: the critical need for field-based hydrogeological research. *Ground Water*, **51(4)**, 488-510.
- Jacobson, M.Z., 2009: Review of solutions to global warming, air pollution, and energy security. *Energy and Environmental Science*, **2(2)**, 148-173.
- Jean, J.-S., H.-R. Guo, S.-H. Chen, C.-C. Liu, W.-T. Chang, Y.-J. Yang, and M.-C. Huang, 2006: The association between rainfall rate and occurrence of an enterovirus epidemic due to a contaminated well. *Journal of Applied Microbiology*, **101(6)**, 1224-1231.
- Jeelani, G., 2008: Aquifer response to regional climate variability in a part of Kashmir Himalaya in India. *Hydrogeology Journal*, **16(8)**, 1625-1633.
- Jiang, F., C. Zhu, G. Mu, R. Hu, and Q. Meng, 2005: Magnification of flood disasters and its relation to regional precipitation and local human activities since the 1980s in Xinjiang, northwestern China. *Natural Hazards*, **36(3)**, 307-330.
- Jiang, T., Z.W. Kundzewicz, and B. Su, 2008: Changes in monthly precipitation and flood hazard in the Yangtze River basin, China. *International Journal of Climatology*, **28(11)**, 1471-1481.
- Jiang, T., T. Fischer, and X.X. Lu, 2013: Larger Asian rivers: changes in hydro-climate and water environments. *Quaternary International*, **304**, 1-4.
- Jiang, X.Y., G.Y. Niu, and Z.L. Yang, 2009: Impacts of vegetation and groundwater dynamics on warm season precipitation over the Central United States. *Journal of Geophysical Research: Atmospheres*, **114**, D06109, doi:10.1029/2008JD010756.
- Jiménez, B.E.C., 2008: Helminths ova control in wastewater and sludge for agricultural reuse. In: *Water and Health Vol. II, Encyclopedia of Life Support Systems (EOLSS)* [Grabow, W. (ed.)]. Developed under the auspices of UNESCO, Eolss Publishers, Oxford, UK, pp. 429-449.
- Jiménez, B.E.C., 2011: Safe sanitation in low economic development areas. In: *Treatise on Water Science, Vol. 4: Water-Quality Engineering* [Wilderer, P. (ed.)]. Elsevier Science and IWA Publishing, London, UK, pp. 147-200.
- Jiménez, B.E.C. and T. Asano (eds.), 2008: *Water Reuse: An International Survey of Current Practice, Issues and Needs*. Scientific and Technical Report No. 20, International Water Association (IWA) Publishing, London, UK, 648 pp.
- Jóhannesson, T., G. Aðalgeirsdóttir, A. Ahlström, L.M. Andreassen, S. Beldring, H. Björnsson, P. Crochet, B. Einarsson, H. Elvehøy, S. Guðmundsson, R. Hock, H. Machguth, K. Melvold, F. Pálsson, V. Radić, O. Sigurðsson, and T. Thorsteinsson, 2012: Hydropower, snow and ice. In: *Climate Change and Energy Systems: Impacts, Risks and Adaptation in the Nordic and Baltic Countries* [Thorsteinsson, T. and H. Björnsson (eds.)]. Nordic Council of Ministers, Copenhagen, Denmark, pp. 91-111.
- Jones, J.A., 2011: Hydrologic responses to climate change: considering geographic context and alternative hypotheses. *Hydrological Processes*, **25(12)**, 1996-2000.
- Jung, I.W. and H. Chang, 2012: Climate change impacts on spatial patterns in drought risk in the Willamette River basin, Oregon, USA. *Theoretical and Applied Climatology*, **108(3-4)**, 355-371.
- Kääb, A., E. Berthier, C. Nuth, J. Gardelle, and Y. Arnaud, 2012: Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. *Nature*, **488(7412)**, 495-498.
- Kalra, A., T.C. Piechota, R. Davies, and G.A. Tootle, 2008: Changes in US streamflow and western US snowpack. *Journal of Hydrologic Engineering*, **13(3)**, 156-163.
- Kaser, G., M. Grosshauser, and B. Marzeion, 2010: Contribution potential of glaciers to water availability in different climate regimes. *Proceedings of the National Academy of Sciences of the United States of America*, **107(47)**, 20223-20227.
- Kashaigili, J.J., K. Rajabu, and P. Masolwa, 2009: Freshwater management and climate change adaptation: experiences from the Great Ruaha River catchment in Tanzania. *Climate and Development*, **1(3)**, 220-228.
- Katul, G. and Novick, K., 2009: Evapotranspiration. In: *Encyclopedia of Inland Waters* [Likens, G.E. (ed.)]. Academic Press, Waltham, MA, USA, pp. 661-667.
- Keller, J., 2008: From microbial fuel cells to bio electrochemical systems: how to convert organic pollutants to electric energy and more. In: *Water and Energy Workshop, 9 September 2008 in Vienna's Austria Centre – Summary* [International Water Association (IWA) (ed.)]. IWA, London, UK, p. 10, www.iwahq.org/ContentSuite/upload/iwa/Document/2008_Vienna_Day2_01.pdf.
- Kharin, V.V., F.W. Zwiers, X. Zhang, and M. Wehner, 2013: Changes in temperature and precipitation extremes in the CMIP5 ensemble. *Climatic Change*, **119(2)**, 345-357.
- Kim, S., Y. Tachikawa, E. Nakakita, and K. Takara, 2009: Reconsideration of reservoir operations under climate change: case study with Yagisawa Dam, Japan. *Annual Journal of Hydraulic Engineering, JSCE*, **53**, 115-120.
- King, C.W., M.E. Webber, and I.J. Duncan, 2010: The water needs for LDV transportation in the United States. *Energy Policy*, **38(2)**, 1157-1167.
- Kingsford, R.T., 2011: Conservation management of rivers and wetlands under climate change – a synthesis. *Marine and Freshwater Research*, **62(3)**, 217-222.
- Kingston, D.G. and R.G. Taylor, 2010: Sources of uncertainty in climate change impacts on river discharge and groundwater in a headwater catchment of the Upper Nile basin, Uganda. *Hydrology and Earth System Sciences*, **14(7)**, 1297-1308.
- Kingston, D.G., M.C. Todd, R.G. Taylor, J.R. Thompson, and N.W. Arnell, 2009: Uncertainty in the estimation of potential evapotranspiration under climate change. *Geophysical Research Letters*, **36**, L20403, doi:10.1029/2009GL040267.
- Kingston, D.G., J.R. Thompson, and G. Kite, 2011: Uncertainty in climate change projections of discharge for the Mekong River basin. *Hydrology and Earth System Sciences*, **15(5)**, 1459-1471.
- Kirshen, P., 2007: *Adaptation Options and Cost in Water Supply*. United Nations Framework Convention on Climate Change, Bonn, Germany, 57 pp.
- Kling, H., M. Fuchs, and M. Paulin, 2012: Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios. *Journal of Hydrology*, **424**, 264-277.

- Knowles, N., M.D. Dettinger, and D.R. Cayan, 2006:** Trends in snowfall versus rainfall in the western United States. *Journal of Climate*, **19(18)**, 4545-4559.
- Knutson, T.R., J.L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J.P. Kossin, A.K. Srivastava, and M. Sugi, 2010:** Tropical cyclones and climate change. *Nature Geoscience*, **3(3)**, 157-163.
- Koboltchnig, G.R., W. Schöner, M. Zappa, and H. Holzmann, 2007:** Contribution of glacier melt to stream runoff: if the climatically extreme summer of 2003 had happened in 1979. *Annals of Glaciology*, **46(1)**, 303-308.
- Koetse, M.J. and P. Rietveld, 2009:** The impact of climate change and weather on transport: an overview of empirical findings. *Transportation Research Part D: Transport and Environment*, **14(3)**, 205-221.
- Konzmann, M., D. Gerten, and J. Heinke, 2013:** Climate impacts on global irrigation requirements under 19 GCMs, simulated with a vegetation and hydrology model. *Hydrological Sciences Journal*, **58**, 1-18.
- Korhonen, J. and E. Kuusisto, 2010:** Long-term changes in the discharge regime in Finland. *Hydrology Research*, **41(3-4)**, 253-268.
- Koutsoyiannis, D., A. Efstratiadis, N. Mamassis, and A. Christofides, 2008:** On the credibility of climate predictions. *Hydrological Sciences Journal*, **53(4)**, 671-684.
- Koutsoyiannis, D., A. Montanari, H.F. Lins, and T.A. Cohn, 2009:** Climate, hydrology and freshwater: towards an interactive incorporation of hydrological experience into climate research. *Hydrological Sciences Journal*, **54(2)**, 394-405.
- Koutsoyiannis, D., A. Christofides, A. Efstratiadis, G.G. Anagnostopoulos, and N. Mamassis, 2011:** Scientific dialogue on climate: is it giving black eyes or opening closed eyes? Reply to "A black eye for the *Hydrological Sciences Journal*" by D. Huard. *Hydrological Sciences Journal*, **56(7)**, 1334-1339.
- Kranz, N., T. Menniken, and J. Hinkel, 2010:** Climate change adaptation strategies in the Mekong and Orange-Senqu basins: what determines the state-of-play? *Environmental Science and Policy*, **13(7)**, 648-659.
- Krysanova, V., C. Dickens, J. Timmerman, C. Varela-Ortega, M. Schlueter, K. Roest, P. Huntjens, F. Jaspers, H. Buiteveld, E. Moreno, J.d.P. Carrera, R. Slamova, M. Martinkova, I. Blanco, P. Esteve, K. Pringle, C. Pahl-Wostl, and P. Kabat, 2010:** Cross-comparison of climate change adaptation strategies across large river basins in Europe, Africa and Asia. *Water Resources Management*, **24(14)**, 4121-4160.
- Kundzewicz, Z.W. and P. Döll, 2009:** Will groundwater ease freshwater stress under climate change? *Hydrological Sciences Journal*, **54(4)**, 665-675.
- Kundzewicz, Z.W. and V. Krysanova, 2010:** Climate change and stream water quality in the multi-factor context. *Climatic Change*, **103(3)**, 353-362.
- Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, P. Kabat, B. Jiménez, K.A. Miller, T. Oki, Z. Sen and I.A. Shiklomanov, 2007:** Freshwater resources and their management. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 173-210.
- Kundzewicz, Z.W., S. Kanae, S.I. Seneviratne, J. Handmer, N. Nicholls, P. Peduzzi, R. Mechler, L.M. Bouwer, N. Arnell, K. Mach, R. Muir-Wood, G. R. Brakenridge, W. Kron, G. Benito, Y. Honda, K. Takahashi, and B. Sherstyukov, 2013:** Flood risk and climate change – global and regional perspectives. *Hydrological Sciences Journal* (in press), doi:10.1080/02626667.2013.857411.
- Kustu, M.D., Y. Fan, and A. Robock, 2010:** Large-scale water cycle perturbation due to irrigation pumping in the US High Plains: a synthesis of observed streamflow changes. *Journal of Hydrology*, **390(3-4)**, 222-244.
- Lambert, F.H., P.A. Stott, M.R. Allen, and M.A. Palmer, 2004:** Detection and attribution of changes in 20th century land precipitation. *Geophysical Research Letters*, **31(10)**, L10203, doi:10.1029/2004GL019545.
- Lawler, D., G. McGregor, and I. Phillips, 2003:** Influence of atmospheric circulation changes and regional climate variability on river flow and suspended sediment fluxes in southern Iceland. *Hydrological Processes*, **17(16)**, 3195-3223.
- Lawrence, D. and I. Haddeland, 2011:** Uncertainty in hydrological modelling of climate impacts in four Norwegian catchments. *Hydrology Research*, **42(6)**, 457-471.
- Lempert, R.J. and D.G. Groves, 2010:** Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west. *Technological Forecasting and Social Change*, **77(6)**, 960-974.
- Lempert, R.J., M.E. Schlesinger, and S.C. Bankes, 1996:** When we don't know the costs or the benefits: adaptive strategies for abating climate change. *Climatic Change*, **33(2)**, 235-274.
- Lempert, R.J., D.G. Groves, S.W. Popper, and S.C. Bankes, 2006:** A general, analytic method for generating robust strategies and narrative scenarios. *Management Science*, **52(4)**, 514-528.
- Li, Z., W. Liu, X. Zhang, and F. Zheng, 2011:** Assessing the site-specific impacts of climate change on hydrology, soil erosion and crop yields in the Loess Plateau of China. *Climatic Change*, **105(1-2)**, 223-242.
- Lins, H.F. and T.A. Cohn, 2011:** Stationarity: wanted dead or alive? *Journal of the American Water Resources Association*, **47(3)**, 475-480.
- Little, M.G. and R.B. Jackson, 2010:** Potential impacts of leakage from deep CO₂ geosequestration on overlying freshwater aquifers. *Environmental Science and Technology*, **44(23)**, 9225-9232.
- Liu, C., R.P. Allan, and G.J. Huffman, 2012:** Co-variation of temperature and precipitation in CMIP5 models and satellite observations. *Geophysical Research Letters*, **39**, L13803, doi:10.1029/2012GL052093.
- Liu, H., 2011:** Impact of climate change on groundwater recharge in dry areas: an ecohydrology approach. *Journal of Hydrology*, **407(1-4)**, 175-183.
- Liu, Y., J. Zhang, G. Wang, J. Liu, R. He, H. Wang, C. Liu, and J. Jin, 2013:** Assessing the effect of climate natural variability in water resources evaluation impacted by climate change. *Hydrological Processes*, **27(7)**, 1061-1071.
- Loaiciga, H.A., T.J. Pingel, and E.S. Garcia, 2012:** Sea water intrusion by sea-level rise: scenarios for the 21st century. *Ground Water*, **50(1)**, 37-47.
- Loos, S., H. Middelkoop, M. van der Perk, and R. van Beek, 2009:** Large scale nutrient modelling using globally available datasets: a test for the Rhine basin. *Journal of Hydrology*, **369(3-4)**, 403-415.
- Lopez, A., F. Fung, M. New, G. Watts, A. Weston, and R.L. Wilby, 2009:** From climate model ensembles to climate change impacts and adaptation: a case study of water resource management in the southwest of England. *Water Resources Research*, **45**, W08419, doi:10.1029/2008WR007499.
- Lu, X.X., S. Zhang, and J. Xu, 2010:** Climate change and sediment flux from the Roof of the World. *Earth Surface Processes and Landforms*, **35(6)**, 732-735.
- Ludwig, F., P. Kabat, H. van Schaik, and M. van der Valk, (eds.) 2009:** *Climate Change Adaptation in the Water Sector*. Earthscan, London, UK, 320 pp.
- MacDonald, A.M., R.C. Carlow, D.M.J. MacDonald, W.G. Darling, and B.É.Ó. Dochartaigh, 2009:** What impact will climate change have on rural groundwater supplies in Africa? *Hydrological Sciences Journal*, **54(4)**, 690-703.
- Mackay, R. and E. Last, 2010:** SWITCH city water balance: a scoping model for integrated urban water management. *Reviews in Environmental Science and Bio-Technology*, **9(4)**, 291-296.
- MacLeod, C.J.A., P.D. Falloon, R. Evans, and P.M. Haygarth, 2012:** Chapter 2: The effects of climate change on the mobilization of diffuse substances from agricultural systems. In: *Advances in Agronomy, Vol. 115* [Sparks, D.L. (ed.)]. Elsevier Science and Technology/Academic Press, Waltham, MA, USA, pp. 41-77.
- Madani, K. and J.R. Lund, 2010:** Estimated impacts of climate warming on California's high-elevation hydropower. *Climatic Change*, **102(3-4)**, 521-538.
- Mahlstein, I., R.W. Portmann, J.S. Daniel, S. Solomon, and R. Knutti, 2012:** Perceptible changes in regional precipitation in a future climate. *Geophysical Research Letters*, **39**, L05701, doi:10.1029/2011GL050738.
- Major, D.C., A. Omojola, M. Dettinger, R.T. Hanson, R. Sanchez-Rodriguez, 2011:** Climate change, water, and wastewater in cities. In: *Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W.D. Solecki, S.A. Hammer, and S. Mehrotra (eds.)]. Cambridge University Press, Cambridge, UK, pp. 113-143.
- Manning, L.J., J.W. Hall, H.J. Fowler, C.G. Kilsby, and C. Tebaldi, 2009:** Using probabilistic climate change information from a multimodel ensemble for water resources. *Water Resources Research*, **45**, W11411, doi:10.1029/2007WR006674.
- Marcé, R., M.T. Rodríguez-Arias, J.C. García, and J. Armengol, 2010:** El Niño Southern Oscillation and climate trends impact reservoir water quality. *Global Change Biology*, **16(10)**, 2857-2865.
- Markoff, M.S. and A.C. Cullen, 2008:** Impact of climate change on Pacific Northwest hydropower. *Climatic Change*, **87(3-4)**, 451-469.
- Marsalek, J., B.E. Jiménez, P.-A. Malmquist, M. Karamouz, J. Goldenfum, and B. Chocat, 2006:** *Urban Water Cycle Processes and Interactions*. International Hydrological Programme, Technical Documents in Hydrology No. 78, United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France, 87 pp.
- Marshall, E. and T. Randhir, 2008:** Effect of climate change on watershed system: a regional analysis. *Climatic Change*, **89(3-4)**, 263-280.
- Masterson, J.P. and S.P. Garabedian, 2007:** Effects of sea-level rise on ground water flow in a coastal aquifer system. *Ground Water*, **45(2)**, 209-217.
- Matthews, J.H. and A.J. Wickel, 2009:** Embracing uncertainty in freshwater climate change adaptation: a natural history approach. *Climate and Development*, **1(3)**, 269-279.

- McCafferty, P.**, 2008: Energy balances in water savings and reuse programs. In: *Water and Energy Workshop, 9 September 2008 in Vienna's Austria Centre – Summary* [International Water Association (IWA) (ed.)]. IWA, London, UK, pp. 4-5, www.iwahq.org/ContentSuite/upload/iwa/Document/2008_Vienna_Day2_01.pdf.
- McDonald, R.I.** and E.H. Givertz, 2013: Two challenges for U.S. irrigation due to climate change: increasing irrigated area in wet states and increasing irrigation rates in dry states. *Plos One*, **8(6)**, e65589, doi:10.1371/journal.pone.0065589.
- McEvoy, J.** and M. Wilder, 2012: Discourse and desalination: potential impacts of proposed climate change adaptation interventions in the Arizona-Sonora border region. *Global Environmental Change: Human and Policy Dimensions*, **22(2)**, 353-363.
- McGuckin, R.**, 2008: Carbon footprints and emerging mitigation/trading regimes. In: *Water and Energy Workshop, 9 September 2008 in Vienna's Austria Centre – Summary* [International Water Association (IWA) (ed.)]. IWA, London, UK, p. 3, www.iwahq.org/ContentSuite/upload/iwa/Document/2008_Vienna_Day2_01.pdf.
- McVicar, T.R.**, T.G. Van Niel, M.L. Roderick, L.T. Li, X.G. Mo, N.E. Zimmermann, and D.R. Schmatz, 2010: Observational evidence from two mountainous regions that near-surface wind speeds are declining more rapidly at higher elevations than lower elevations: 1960-2006. *Geophysical Research Letters*, **37**, L06402, doi:10.1029/2009GL042255.
- Medellin-Azuares, J.**, J.J. Harou, M.A. Olivares, K. Madani, J.R. Lund, R.E. Howitt, S.K. Tanaka, M.W. Jenkins, and T. Zhu, 2008: Adaptability and adaptations of California's water supply system to dry climate warming. *Climatic Change*, **87**, 575-590.
- Mertz, O.**, K. Halsnæs, J.E. Olesen, and K. Rasmussen, 2009: Adaptation to climate change in developing countries. *Environmental Management*, **43(5)**, 743-752.
- Miao, C.**, J. Ni, A.G.L. Borthwick, and L. Yang, 2011: A preliminary estimate of human and natural contributions to the changes in water discharge and sediment load in the Yellow River. *Global and Planetary Change*, **76(3-4)**, 196-205.
- Miles, E.L.**, M.M. Elsner, J.S. Littell, L.W. Binder, and D.P. Lettenmaier, 2010: Assessing regional impacts and adaptation strategies for climate change: the Washington climate change impacts assessment. *Climatic Change*, **102(1-2)**, 9-27.
- Millennium Ecosystem Assessment**, 2005: *Ecosystems and Human Well-being: Wetlands and Water: Synthesis*. A Report of the Millennium Ecosystem Assessment, World Resources Institute, Washington DC, USA, 68 pp.
- Milly, P.C.D.** and K.A. Dunne, 2011: On the hydrologic adjustment of climate-model projections: the potential pitfall of potential evapotranspiration. *Earth Interactions*, **15**, doi: <http://dx.doi.org/10.1175/2010EI363.1>.
- Min, S.**, X. Zhang, F.W. Zwiers, and G.C. Hegerl, 2011: Human contribution to more-intense precipitation extremes. *Nature*, **470(7334)**, 378-381.
- Minville, M.**, F. Brissette, S. Krau, and R. Leconte, 2009: Adaptation to climate change in the management of a Canadian water-resources system exploited for hydropower. *Water Resources Management*, **23(14)**, 2965-2986.
- Miralles, D.G.**, T.R.H. Holmes, R.A.M. De Jeu, J.H. Gash, A.G.C.A. Meesters, and A.J. Dolman, 2011: Global land-surface evaporation estimated from satellite-based observations. *Hydrology and Earth System Sciences*, **15(2)**, 453-469.
- MLIT** (Ministry of Land, Infrastructure, Transportation and Tourism in Japan), 2011: *Water Resources in Japan*. <http://www.mlit.go.jp/common/000160806.pdf>.
- Mogaka, H.**, S. Gichere, R. Davis, and R. Hirji, 2006: *Climate Variability and Water Resources Degradation in Kenya: Improving Water Resources Development and Management*. World Bank Working Paper No. 69, The International Bank for Reconstruction and Development / The World Bank, Washington DC, USA, 108 pp.
- Montenegro, A.** and R. Ragab, 2010: Hydrological response of a Brazilian semi-arid catchment to different land use and climate change scenarios: a modelling study. *Hydrological Processes*, **24(19)**, 2705-2723.
- Mudelsee, M.**, M. Borngen, G. Tetzlaff, and U. Grunewald, 2003: No upward trends in the occurrence of extreme floods in central Europe. *Nature*, **425(6954)**, 166-169.
- Muerth, M.J.**, B.G. St-Denis, S. Ricard, J.A. Velazquez, J. Schmid, M. Minville, D. Caya, D. Chaumont, R. Ludwig, and R. Turcotte, 2013: On the need for bias correction in regional climate scenarios to assess climate change impacts on river runoff. *Hydrology and Earth System Sciences*, **17(3)**, 1189-1204.
- Muller, M.**, 2007: Adapting to climate change: water management for urban resilience. *Environment and Urbanization*, **19(1)**, 99-113.
- Mukhopadhyay, B.** and A. Dutta, 2010: A stream water availability model of upper Indus basin based on a topologic model and global climatic datasets. *Water Resources Management*, **24(15)**, 4403-4443.
- Munasinghe, M.**, 2009: Integrated solutions for water, sustainable development and climate change issues: applying the sustainability framework. In: *On the Water Front* [Lundqvist, J. (ed.)]. Selections from the 2009 World Water Week, Stockholm International Water Institute, Stockholm, Sweden, pp. 46-55.
- Murray, S.J.**, P.N. Foster, and I.C. Prentice, 2012: Future global water resources with respect to climate change and water withdrawals as estimated by a dynamic global vegetation model. *Journal of Hydrology*, **448-449**, 14-29.
- Mysiak, J.**, H.J. Henrikson, C. Sullivan, J. Bromley, and C. Pahl-Wostl (eds.), 2009: *The Adaptive Water Resources Management Handbook*. Earthscan, London, UK, 199 pp.
- NACWA**, 2009: *Confronting Climate Change: An Early Analysis of Water and Wastewater Adaptation Costs*. National Association of Clean Water Agencies, Washington DC, USA, 104 pp.
- Nakaegawa, T.**, A. Kitoh, M. Hosaka, 2013: Discharge of major global rivers in the late 21st century climate projected with the high horizontal resolution MRI-AGCMs. *Hydrological Processes*, **27(23)**, 3301-3318.
- Nassopoulos, H.**, P. Dumas, and S. Hallegatte, 2012: Adaptation to an uncertain climate change: cost benefit analysis and robust decision making for dam dimensioning. *Climatic Change*, **114(3-4)**, 497-508.
- Neupane, R.P.** and J.D. White, 2010: *Simulation of Climate Change Impacts on Himalayan Headwater Watershed Snowmelt Hydrology: Discharge, Sediment Load, and Nutrient Shifts*. Presentation at the 2010 Fall Meeting, American Geophysical Union (AGU), 13-17 December, San Francisco, CA, USA, Abstract No. H43F-1318, abstractsearch.agu.org/meetings/2010/FM/sections/H/sessions/H43F/abstracts/H43F-1318.html.
- Ng, G.-H.C.**, D. McLaughlin, D. Entekhabi, and B.R. Scanlon, 2010: Probabilistic analysis of the effects of climate change on groundwater recharge. *Water Resources Research*, **46**, W07502, doi:10.1029/2009WR007904.
- Nicot, J.-P.**, 2008: Evaluation of large-scale CO₂ storage on fresh-water sections of aquifers: an example from the Texas Gulf Coast basin. *International Journal of Greenhouse Gas Control*, **2(4)**, 582-593.
- Noake, K.**, D. Polson, G. Hegerl, and X. Zhang, 2012: Changes in seasonal land precipitation during the latter twentieth-century. *Geophysical Research Letters*, **39**, L03706, doi:10.1029/2011GL050405.
- Nobrega, M.T.**, W. Collischonn, C.E.M. Tucci, and A.R. Paz, 2011: Uncertainty in climate change impacts on water resources in the Rio Grande basin, Brazil. *Hydrology and Earth System Sciences*, **15(2)**, 585-595.
- Nyman, P.**, G.J. Sheridan, H.G. Smith, and P.N.J. Lane, 2011: Evidence of debris flow occurrence after wildfire in upland catchments of south-east Australia. *Geomorphology*, **125(3)**, 383-401.
- OECD**, 2010: *Cities and Climate Change*. Organisation for Economic Co-operation and Development (OECD), OECD Publishing, Paris, France, 274 pp., doi:10.1787/9789264091375-en.
- OFWAT**, 2009: *Climate Change – Good Practice from the 2009 Price Review: Water Today, Water Tomorrow*. The Water Services Regulation Authority (OFWAT), Birmingham, UK, 36 pp.
- O'Gorman, P.A.**, 2012: Sensitivity of tropical precipitation extremes to climate change. *Nature Geoscience*, **5(10)**, 697-700.
- Okazaki, A.**, P.J.-F. Yeh, K. Yoshimura, M. Watanabe, M. Kimoto, and T. Oki, 2012: Changes in flood risk under global warming estimated using MIROC5 and the discharge probability index. *Journal of the Meteorological Society of Japan*, **90(4)**, 509-524.
- Oki, T.** and S. Kanae, 2006: Global hydrological cycles and world water resources. *Science*, **313(5790)**, 1068-1072.
- Olhoff, A.** and C. Schaer, 2010: *Screening Tools and Guidelines to Support the Mainstreaming of Climate Change Adaptation into Development Assistance – A Stocktaking Report*. United Nations Development Programme (UNDP), New York, NY, USA, 48 pp.
- Olsson, J.**, W. Yang, L.P. Graham, J. Rosberg, and J. Andreasson, 2011: Using an ensemble of climate projections for simulating recent and near-future hydrological change to Lake Vanern in Sweden. *Tellus Series A – Dynamic Meteorology and Oceanography*, **63(1)**, 126-137.
- Orlowsky, B.** and S.I. Seneviratne, 2013: Elusive drought: uncertainty in observed trends and short- and long-term CMIP5 projections. *Hydrology and Earth System Sciences*, **17(5)**, 1765-1781.
- Oude Essink, G. H. P.**, E.S. van Baaren, and de Louw, P. G. B., 2010: Effects of climate change on coastal groundwater systems: a modeling study in the Netherlands. *Water Resources Research*, **46(10)**, W00F04, doi:10.1029/2009WR008719.
- Ozaki, N.**, T. Fukushima, H. Harasawa, T. Kojiri, K. Kawashima, and M. Ono, 2003: Statistical analyses on the effects of air temperature fluctuations on river water qualities. *Hydrological Processes*, **17(14)**, 2837-2853.
- Paerl, H.W.** and J. Huisman, 2008: Climate – blooms like it hot. *Science*, **320(5872)**, 57-58.

- Paerl, H.W., L.M. Valdes, M.F. Piehler, and C.A. Stow, 2006: Assessing the effects of nutrient management in an estuary experiencing climatic change: the Neuse River Estuary, North Carolina. *Environmental Management*, **37**(3), 422-436.
- Pahl-Wostl, C., 2007: Transitions towards adaptive management of water facing climate and global change. *Water Resources Management*, **21**(1), 49-62.
- Pahl-Wostl, C., P. Kabat, and J. Moltgen (eds.), 2008: *Adaptive and Integrated Water Management: Coping with Complexity and Uncertainty*. Springer Berlin Heidelberg Germany, 440 pp.
- Pall, P., T. Aina, D.A. Stone, P.A. Stott, T. Nozawa, A.G.J. Hilberts, D. Lohmann, and M.R. Allen, 2011: Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature*, **470**(7334), 382-385.
- Pednekar, A.M., S.B. Grant, Y. Jeong, Y. Poon, and C. Oancea, 2005: Influence of climate change, tidal mixing, and watershed urbanization on historical water quality in Newport Bay, a saltwater wetland and tidal embayment in southern California. *Environmental Science and Technology*, **39**(23), 9071-9082.
- Pekarova, P., D. Halmova, P. Miklanek, M. Onderka, J. Pekar, and P. Skoda, 2008: Is the water temperature of the Danube River at Bratislava, Slovakia, rising? *Journal of Hydrometeorology*, **9**(5), 1115-1122.
- Petley, D., 2012: Global patterns of loss of life from landslides. *Geology*, **40**(10), 927-930.
- Petrow, T. and B. Merz, 2009: Trends in flood magnitude, frequency and seasonality in Germany in the period 1951-2002. *Journal of Hydrology*, **371**(1-4), 129-141.
- Petrow, T., J. Zimmer, and B. Merz, 2009: Changes in the flood hazard in Germany through changing frequency and persistence of circulation patterns. *Natural Hazards and Earth System Sciences*, **9**(4), 1409-1423.
- Piani, C., J.O. Haerter, and E. Coppola, 2010: Statistical bias correction for daily precipitation in regional climate models over Europe. *Theoretical and Applied Climatology*, **99**(1-2), 187-192.
- Piao, S., P. Friedlingstein, P. Ciais, N. de Noblet-Ducoudre, D. Labat, and S. Zaehle, 2007: Changes in climate and land use have a larger direct impact than rising CO₂ on global river runoff trends. *Proceedings of the National Academy of Sciences of the United States of America*, **104**(39), 15242-15247.
- Piao, S., P. Ciais, Y. Huang, Z. Shen, S. Peng, J. Li, L. Zhou, H. Liu, Y. Ma, Y. Ding, P. Friedlingstein, C. Liu, K. Tan, Y. Yu, T. Zhang, and J. Fang, 2010: The impacts of climate change on water resources and agriculture in China. *Nature*, **467**(7311), 43-51.
- Pinter, N., B.S. Ickes, J.H. Wlosinski, and R.R. van der Ploeg, 2006: Trends in flood stages: contrasting results from the Mississippi and Rhine River systems. *Journal of Hydrology*, **331**(3-4), 554-566.
- Pittock, J. and C.M. Finlayson, 2011: Australia's Murray-Darling basin: freshwater ecosystem conservation options in an era of climate change. *Marine and Freshwater Research*, **62**(3), 232-243.
- Poff, N.L. and J.K.H. Zimmerman, 2010: Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology*, **55**(1), 194-205.
- Portmann, F.T., P. Döll, S. Eisner, and M. Flörke, 2013: Impact of climate change on renewable groundwater resources: assessing the benefits of avoided greenhouse gas emissions using selected CMIP5 climate projections. *Environmental Research Letters*, **8**(2), 024023, doi:10.1088/1748-9326/8/2/024023.
- Prudhomme, C., R.L. Wilby, S. Crooks, A.L. Kay, and N.S. Reynard, 2010: Scenario-neutral approach to climate change impact studies: application to flood risk. *Journal of Hydrology*, **390**(3-4), 198-209.
- Prudhomme, C., S. Parry, J. Hannaford, D.B. Clark, S. Hagemann, and F. Voss, 2011: How well do large-scale models reproduce regional hydrological extremes in Europe? *Journal of Hydrometeorology*, **12**(6), 1181-1204.
- Qian, Y., M.G. Flanner, L.R. Leung, and W. Wang, 2011: Sensitivity studies on the impacts of Tibetan Plateau snowpack pollution on the Asian hydrological cycle and monsoon climate. *Atmospheric Chemistry and Physics*, **11**(5), 1929-1948.
- Qin, B., G. Zhu, G. Gao, Y. Zhang, W. Li, H.W. Paerl, and W.W. Carmichael, 2010: A drinking water crisis in Lake Taihu, China: linkage to climatic variability and lake management. *Environmental Management*, **45**(1), 105-112.
- Quintana Seguí, P., A. Ribes, E. Martin, F. Habets, and J. Boe, 2010: Comparison of three downscaling methods in simulating the impact of climate change on the hydrology of Mediterranean basins. *Journal of Hydrology*, **383**(1-2), 111-124.
- Rabassa, J., 2009: Impact of global climate change on glaciers and permafrost of South America, with emphasis on Patagonia, Tierra del Fuego, and the Antarctic Peninsula. *Developments in Earth Surface Processes*, **13**, 415-438.
- Rabatel, A., B. Francou, A. Soruco, J. Gomez, B. Caceres, J.L. Ceballos, R. Basantes, M. Vuille, J.-E. Sicart, C. Huggel, M. Scheel, Y. Lejeune, Y. Arnaud, M. Collet, T. Condom, G. Consoli, V. Favier, V. Jomelli, R. Galarraga, P. Ginot, L. Maisincho, J. Mendoza, M. Menegoz, E. Ramirez, P. Ribstein, W. Suarez, M. Villacis, and P. Wagnon, 2013: Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change. *Cryosphere*, **7**(1), 81-102.
- Radić, V., A. Bliss, A.C. Beedlow, R. Hock, E. Miles, and J.G. Cogley, 2013: Regional and global projections of the 21st century glacier mass changes in response to climate scenarios from GCMs. *Climate Dynamics* (in press), doi:10.1007/s00382-013-1719-7.
- Raje, D. and P.P. Mujumdar, 2010: Reservoir performance under uncertainty in hydrologic impacts of climate change. *Advances in Water Resources*, **33**(3), 312-326.
- Ramírez, A., S. Hagedoorn, L. Kramers, T. Wildenborg, and C. Hendriks, 2010: Screening CO₂ storage options in The Netherlands. *International Journal of Greenhouse Gas Control*, **4**(2), 367-380.
- Rehana, S. and P.P. Mujumdar, 2012: Climate change induced risk in water quality control problems. *Journal of Hydrology*, **444**, 63-77.
- Reiter, P., 2009: *Cities of the Future and Water: Can We Reshape Urban Water and Urban Design to Achieve Long Term Water Security?* Presentation from the 2009 World Water Week, 16-22 August, in Stockholm, Sweden, 68 pp., www.worldwaterweek.org/documents/WWW_PDF/2009/tuesday/T4/future/Reiter_Stockholm_2009_COF_Opening.pdf.
- Renner, M. and C. Bernhofer, 2012: Applying simple water-energy balance frameworks to predict the climate sensitivity of streamflow over the continental United States. *Hydrology and Earth System Sciences*, **16**(8), 2531-2546.
- Renner, M., R. Seppelt, and C. Bernhofer, 2012: Evaluation of water-energy balance frameworks to predict the sensitivity of streamflow to climate change. *Hydrology and Earth System Sciences*, **16**(5), 1419-1433.
- Renofalt, B.M., R. Jansson, and C. Nilsson, 2010: Effects of hydropower generation and opportunities for environmental flow management in Swedish riverine ecosystems. *Freshwater Biology*, **55**(1), 49-67.
- Rosenzweig, C., G. Casassa, D.J. Karoly, A. Imeson, C. Liu, A. Menzel, S. Rawlins, T.L. Root, B. Seguin, and P. Tryjanowski, 2007: Assessment of observed changes and responses in natural and managed systems. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 79-131.
- Rost, S., D. Gerten, H. Hoff, W. Lucht, M. Falkenmark, and J. Rockstrom, 2009: Global potential to increase crop production through water management in rainfed agriculture. *Environmental Research Letters*, **4**(4), 044002, doi:10.1088/1748-9326/4/4/044002.
- Rozell, D.J. and S.J. Reaven, 2012: Water pollution risk associated with natural gas extraction from the Marcellus Shale. *Risk Analysis*, **32**(8), 1382-1393.
- Rozemeijer, J.C., H.P. Broers, F.C. van Geer, and M.F.P. Bierkens, 2009: Weather-induced temporal variations in nitrate concentrations in shallow groundwater. *Journal of Hydrology*, **378**(1-2), 119-127.
- Rudberg, P.M., O. Wallgren, and A.G. Swartling, 2012: Beyond generic adaptive capacity: exploring the adaptation space of the water supply and wastewater sector of the Stockholm region, Sweden. *Climatic Change*, **114**(3-4), 707-721.
- Saarinen, T., K.-M. Vuori, E. Alasaarela, and B. Kløve, 2010: Long-term trends and variation of acidity, COD_{Mn}, and colour in coastal rivers of western Finland in relation to climate and hydrology. *Science of the Total Environment*, **408**(21), 5019-5027.
- Sadoff, C. and M. Muller, 2009: *Water Management, Water Security and Climate Change Adaptation: Early Impacts and Essential Responses*. Global Water Partnership Technical Committee (TEC) Background Paper No. 14, Global Water Partnership, Stockholm, Sweden, 85 pp.
- Sahoo, G.B., S.G. Schladow, J.E. Reuter, and R. Coats, 2010: Effects of climate change on thermal properties of lakes and reservoirs, and possible implications. *Stochastic Environmental Research and Risk Assessment*, **25**(4), 445-456.
- Schewe, J., J. Heinke, D. Gerten, I. Haddeland, N.W. Arnell, D.B. Clark, R. Dankers, S. Eisner, B. Fekete, F.J. Colón-González, S.N. Gosling, H. Kim, X. Liu, Y. Masaki, F.T. Portmann, Y. Satoh, T. Stacke, Q. Tang, Y. Wada, D. Wisser, T. Albrecht, K. Frieler, F. Piontek, L. Warszawski, and P. Kabat, 2013: Multi-model assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences of the United States of America* (in press), doi:10.1073/pnas.1222460110.
- Scholz, G., J.N. Quinton, and P. Strauss, 2008: Soil erosion from sugar beet in central Europe in response to climate change induced seasonal precipitation variations. *Catena*, **72**(1), 91-105.

- Schwartz, J., R. Levin, and R. Goldstein, 2000: Drinking water turbidity and gastrointestinal illness in the elderly of Philadelphia. *Journal of Epidemiology and Community Health*, **54**(1), 45-51.
- Seah, H., 2008: Energy balances in advanced treatment for new water. In: *Water and Energy Workshop, 9 September 2008 in Vienna's Austria Centre – Summary* [International Water Association (IWA) (ed.)]. IWA, London, UK, p. 3, www.iwahq.org/ContentSuite/upload/iwa/Document/2008_Vienna_Day2_01.pdf.
- Seidu, R., T.A. Stenström, and L. Owe, 2013: A comparative cohort study of the effect of rainfall and temperature on diarrhoeal disease in faecal sludge and non-faecal sludge applying communities, Northern Ghana. *Journal of Water and Climate Change*, **4**(2), 90-102.
- Seneviratne, S.I., D. Lüthi, M. Litschi, and C. Schär, 2006: Land-atmosphere coupling and climate change in Europe. *Nature*, **443**(7108), 205-209.
- Seneviratne, S.I., T. Corti, E.L. Davin, M. Hirschi, E.B. Jaeger, I. Lehner, B. Orlowsky, and A.J. Teuling, 2010: Investigating soil moisture-climate interactions in a changing climate: A review. *Earth-Science Reviews*, **99**(3-4), 125-161.
- Seneviratne, S.I., N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, and X. Zhang, 2012: Changes in climate extremes and their impacts on the natural physical environment. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 109-230.
- Senhorst, H.A.J. and J.J.G. Zwolsman, 2005: Climate change and effects on water quality: a first impression. *Water Science and Technology*, **51**(5), 53-59.
- Sheffield, J. and E.F. Wood, 2008: Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. *Climate Dynamics*, **31**(1), 79-105.
- Shiklomanov, A.I., R.B. Lammers, M.A. Rawlins, L.C. Smith, and T.M. Pavelsky, 2007: Temporal and spatial variations in maximum river discharge from a new Russian data set. *Journal of Geophysical Research-Biogeosciences*, **112**(G4), G04S53, doi:10.1029/2006JG000352.
- Short, M.D., W.L. Peirson, G.M. Peters, and R.J. Cox, 2012: Managing adaptation of urban water systems in a changing climate. *Water Resources Management*, **26**(7), 1953-1981.
- Sigel, K., B. Klauer, and C. Pahl-Wostl, 2010: Conceptualising uncertainty in environmental decision-making: the example of the EU Water Framework Directive. *Ecological Economics*, **69**(3), 502-510.
- Skaugen, T., H.B. Stranden, and T. Saloranta, 2012: Trends in snow water equivalent in Norway (1931-2009). *Hydrology Research*, **43**(4), 489-499.
- Smith, H.G., G.J. Sheridan, P.N.J. Lane, P. Nyman, and S. Haydon, 2011: Wildfire effects on water quality in forest catchments: a review with implications for water supply. *Journal of Hydrology*, **396**(1-2), 170-192.
- Smith, L.C., 2000: Trends in Russian Arctic river-ice formation and breakup, 1917 to 1994. *Physical Geography*, **21**(1), 46-56.
- Sprenger, C., G. Lorenzen, I. Hülshoff, G. Grützmacher, M. Ronghang, and A. Pekdeger, 2011: Vulnerability of bank filtration systems to climate change. *Science of the Total Environment*, **409**(4), 655-663.
- Stahl, K., H. Hisdal, J. Hannaford, L.M. Tallaksen, H.A.J. van Lanen, E. Sauquet, S. Demuth, M. Fendekova, and J. Jodar, 2010: Streamflow trends in Europe: evidence from a dataset of near-natural catchments. *Hydrology and Earth System Sciences*, **14**(12), 2367-2382.
- Stahl, K., L.M. Tallaksen, J. Hannaford, and H.A.J. van Lanen, 2012: Filling the white space on maps of European runoff trends: estimates from a multi-model ensemble. *Hydrology and Earth System Sciences*, **16**(7), 2035-2047.
- Stainforth, D.A., M.R. Allen, E.R. Tredger, and L.A. Smith, 2007: Confidence, uncertainty and decision-support relevance in climate predictions. *Philosophical Transactions of the Royal Society A*, **365**(1857), 2145-2161.
- Stakhiv, E.Z., 2011: Pragmatic approaches for water management under climate change uncertainty. *Journal of the American Water Resources Association*, **47**(6), 1183-1196.
- Steele-Dunne, S., P. Lynch, R. McGrath, T. Semmler, S. Wang, J. Hanafin, and P. Nolan, 2008: The impacts of climate change on hydrology in Ireland. *Journal of Hydrology*, **356**(1-2), 28-45.
- Stoll, S., H.J.H. Franssen, R. Barthel, and W. Kinzelbach, 2011: What can we learn from long-term groundwater data to improve climate change impact studies? *Hydrology and Earth System Sciences*, **15**(12), 3861-3875.
- Stott, P.A., N.P. Gillett, G.C. Hegerl, D.J. Karoly, D.A. Stone, X. Zhang, and F. Zwiers, 2010: Detection and attribution of climate change: a regional perspective. *Wiley Interdisciplinary Reviews: Climate Change*, **1**(2), 192-211.
- Stuart-Hill, S.I. and R.E. Schulze, 2010: Does South Africa's water law and policy allow for climate change adaptation? *Climate and Development*, **2**(2), 128-144.
- Sun, F., M.L. Roderick, and G.D. Farquhar, 2012: Changes in the variability of global land precipitation. *Geophysical Research Letters*, **39**, L19402, doi:10.1029/2012GL053369.
- Takala, M., J. Pulliainen, S.J. Metsamaki, and J.T. Koskinen, 2009: Detection of snowmelt using spaceborne microwave radiometer data in Eurasia from 1979 to 2007. *IEEE Transactions on Geoscience and Remote Sensing*, **47**(9), 2996-3007.
- Tan, A., J.C. Adam, and D.P. Lettenmaier, 2011: Change in spring snowmelt timing in Eurasian Arctic rivers. *Journal of Geophysical Research: Atmospheres*, **116**, D03101, doi:10.1029/2010JD014337.
- Tang, Q. and D.P. Lettenmaier, 2012: 21st century runoff sensitivities of major global river basins. *Geophysical Research Letters*, **39**, L06403, doi:10.1029/2011GL050834.
- Taylor, I.H., E. Burke, L. McColl, P.D. Falloon, G.R. Harris, and D. McNeall, 2013: The impact of climate mitigation on projections of future drought. *Hydrology and Earth System Sciences*, **17**(6), 2339-2358.
- Taylor, R., M. Miret-Gaspa, J. Tumwine, L. Mileham, R. Flynn, G. Howard, and R. Kulabako, 2009: Increased risk of diarrhoeal diseases from climate change: evidence from communities supplied by groundwater in Uganda. In: *Groundwater and Climate in Africa* [Taylor, R., C. Tindimugaya, M. Owor, and M. Shamsudduha (eds.)]. Proceedings of the Kampala Conference, 24-28 June 2008, International Association of Hydrological Sciences (IAHS), IAHS Publication No. 334, IAHS Press, Wallingford, UK, pp. 15-19.
- Taylor, R.G., B. Scanlon, P. Döll, M. Rodell, R. van Beek, Y. Wada, L. Longuevergne, M. Leblanc, J.S. Famiglietti, M. Edmunds, L. Konikow, T.R. Green, J. Chen, M. Taniguchi, M.F.P. Bierkens, A. MacDonald, Y. Fan, R.M. Maxwell, Y. Yechieli, J.J. Gurdak, D.M. Allen, M. Shamsudduha, K. Hiscock, P.J.-F. Yeh, I. Holman, and H. Treidel, 2013a: Ground water and climate change. *Nature Climate Change*, **3**(4), 322-329.
- Taylor, R.G., M.C. Todd, L. Kongola, L. Maurice, E. Nahozya, H. Sanga, and A.M. MacDonald, 2013b: Evidence of the dependence of groundwater resources on extreme rainfall in East Africa. *Nature Climate Change*, **3**(4), 374-378.
- Tchobanoglous, G., F.L. Burton, and H.D. Stensel (eds.), 2003: *Wastewater Engineering: Treatment and Reuse*. McGraw-Hill Education, Columbus, OH, USA, 1819 pp.
- Teng, J., J. Vaze, F.H.S. Chiew, B. Wang, and J. Perraud, 2012: Estimating the relative uncertainties sourced from GCMs and hydrological models in modeling climate change impact on runoff. *Journal of Hydrometeorology*, **13**(1), 122-139.
- Tetzlaff, D., C. Soulsby, and C. Birkel, 2010: Hydrological connectivity and microbiological fluxes in montane catchments: the role of seasonality and climatic variability. *Hydrological Processes*, **24**(9), 1231-1235.
- Teutschbein, C. and J. Seibert, 2012: Bias correction of regional climate model simulations for hydrological climate-change impact studies: review and evaluation of different methods. *Journal of Hydrology*, **456**, 12-29.
- Thodsen, H., B. Hasholt, and J.H. Kjærsgaard, 2008: The influence of climate change on suspended sediment transport in Danish rivers. *Hydrological Processes*, **22**(6), 764-774.
- Thöle, D., 2008: Ways to identify possibilities of energy saving at wastewater treatment plants. In: *Water and Energy Workshop, 9 September 2008 in Vienna's Austria Centre – Summary* [International Water Association (IWA) (ed.)]. IWA, London, UK, pp. 5-6, www.iwahq.org/ContentSuite/upload/iwa/Document/2008_Vienna_Day2_01.pdf.
- Thorne, O. and R.A. Fenner, 2011: The impact of climate change on reservoir water quality and water treatment plant operations: a UK case study. *Water and Environment Journal*, **25**(1), 74-87.
- Thorne, R., 2011: Uncertainty in the impacts of projected climate change on the hydrology of a subarctic environment: Liard River basin. *Hydrology and Earth System Sciences*, **15**(5), 1483-1492.
- Tibby, J. and D. Tiller, 2007: Climate-water quality relationships in three western Victorian (Australia) lakes 1984-2000. *Hydrobiologia*, **591**(1), 219-234.
- Towler, E., B. Rajagopalan, E. Gilleland, R.S. Summers, D. Yates, and R.W. Katz, 2010: Modeling hydrologic and water quality extremes in a changing climate: A statistical approach based on extreme value theory. *Water Resources Research*, **46**(11), W11504, doi:10.1029/2009WR008876.

- Trabucco, A., R.J. Zomer, D.A. Bossio, O. van Straaten, and L.V. Verchot, 2008:** Climate change mitigation through afforestation/reforestation: a global analysis of hydrologic impacts with four case studies. *Agriculture Ecosystems and Environment*, **126(1-2)**, 81-97.
- Trolle, D., D.P. Hamilton, C.A. Pilditch, I.C. Duggan, and E. Jeppesen, 2011:** Predicting the effects of climate change on trophic status of three morphologically varying lakes: implications for lake restoration and management. *Environmental Modelling and Software*, **26(4)**, 354-370.
- Tumwine, J., A. Kekitiinwa, N. Nabukeera, D. Akiyoshi, M. Buckholt, and S. Tzipori, 2002:** Enterocytotoxin bieneusi among children with diarrhea attending Mulago Hospital in Uganda. *American Journal of Tropical Medicine and Hygiene*, **67(3)**, 299-303.
- Tumwine, J., A. Kekitiinwa, N. Nabukeera, D. Akiyoshi, S. Rich, G. Widmer, X. Feng, and S. Tzipori, 2003:** Cryptosporidium parvum in children with diarrhea in Mulago Hospital, Kampala, Uganda. *American Journal of Tropical Medicine and Hygiene*, **68(6)**, 710-715.
- UN, 2011:** *World Population Prospects: The 2010 Revision*. United Nations, New York, NY, USA, 481 pp.
- UNECE, 2009:** *Guidance on Water and Adaptation to Climate Change*. United Nations Economic Commission for Europe (UNECE), Geneva, Switzerland, 127 pp.
- UNESCO, 2011:** *The Impact of Global Change on Water Resources: The Response of UNESCO'S International Hydrology Programme*. United Nations Educational Scientific and Cultural Organization (UNESCO) International Hydrological Programme (IHP), Paris, France, 20 pp.
- UNFCCC, 2007:** *Investments and Financial Flows to Address Climate Change*. United Nations Framework Convention on Climate Change, Bonn, Germany, 272 pp.
- UN-HABITAT, 2008:** *State of the World's Cities 2010/2011: Bridging the Urban Divide*. United Nations Human Settlements Programme (UN-HABITAT), Nairobi, Kenya, 224 pp.
- Utsumi, N., S. Seto, S. Kanae, E.E. Maeda, and T. Oki, 2011:** Does higher surface temperature intensify extreme precipitation? *Geophysical Research Letters*, **38(16)**, L16708, doi:10.1029/2011GL048426.
- van Dijk, A.I.J.M. and R.J. Keenan, 2007:** Planted forests and water in perspective. *Forest Ecology and Management*, **251(1-2)**, 1-9.
- van Huijgevoort, M.H.J., P. Hazenberg, H.A.J. van Lanen, A.J. Teuling, D.B. Clark, S. Folwell, S.N. Gosling, N. Hanasaki, J. Heinke, S. Koirala, T. Stacke, F. Voss, J. Sheffield, and R. Uijlenhoet, 2013:** Global multi-model analysis of drought in runoff for the second half of the 20th century. *Journal of Hydrometeorology*, **14(5)**, 1535-1552.
- van Pelt, S.C., P. Kabat, H.W. ter Maat, B.J.J.M. van den Hurk, and A.H. Weerts, 2009:** Discharge simulations performed with a hydrological model using bias corrected regional climate model input. *Hydrology and Earth System Sciences*, **13(12)**, 2387-2397.
- van Roosmalen, L., B.S.B. Christensen, and T.O. Sonnenborg, 2007:** Regional differences in climate change impacts on groundwater and stream discharge in Denmark. *Vadose Zone Journal*, **6(3)**, 554-571.
- van Vliet, M.T.H. and J.J.G. Zwolsman, 2008:** Impact of summer droughts on the water quality of the Meuse river. *Journal of Hydrology*, **353(1-2)**, 1-17.
- van Vliet, M.T.H., J.R. Yearsley, F. Ludwig, S. Voegelé, D.P. Lettenmaier, and P. Kabat, 2012:** Vulnerability of US and European electricity supply to climate change. *Nature Climate Change*, **2(9)**, 676-681.
- van Vuuren, D.P., K. Riahi, R. Moss, J. Edmonds, A. Thomson, N. Nakicenovic, T. Kram, F. Berkhout, R. Swart, A. Janetos, S.K. Rose, and N. Arnell, 2012:** A proposal for a new scenario framework to support research and assessment in different climate research communities. *Global Environmental Change: Human and Policy Dimensions*, **22(1)**, 21-35.
- Vaze, J., D.A. Post, F.H.S. Chiew, J.-M. Perraud, N.R. Viney, and J. Teng, 2010:** Climate non-stationarity – validity of calibrated rainfall-runoff models for use in climate change studies. *Journal of Hydrology*, **394(3-4)**, 447-457.
- Veijalainen, N., J. Korhonen, B. Vehviläinen, and H. Koivusalo, 2012:** Modelling and statistical analysis of catchment water balance and discharge in Finland in 1951-2009 using transient climate scenarios. *Journal of Water and Climate Change*, **3(1)**, 55-78.
- Ventela, A., T. Kirkkala, A. Lendasse, M. Tarvainen, H. Helminen, and J. Sarvala, 2011:** Climate-related challenges in long-term management of Säkylän Pyhäjärvi (SW Finland). *Hydrobiologia*, **660(1)**, 49-58.
- Vidal, J.-P., E. Martin, N. Kitova, J. Najac, and J.-M. Soubeyrou, 2012:** Evolution of spatio-temporal drought characteristics: validation, projections and effect of adaptation scenarios. *Hydrology and Earth System Sciences*, **16(8)**, 2935-2955.
- Viviroli, D., D.R. Archer, W. Buytaert, H.J. Fowler, G.B. Greenwood, A.F. Hamlet, Y. Huang, G. Koboltschnig, M.I. Litaor, J.I. López-Moreno, S. Lorentz, B. Schädler, H. Schreier, K. Schwaiger, M. Vuille, and R. Woods, 2011:** Climate change and mountain water resources: overview and recommendations for research, management and policy. *Hydrology and Earth System Sciences*, **15(2)**, 471-504.
- Vörösmarty, C., P. Green, J. Salisbury, and R. Lammers, 2000:** Global water resources: vulnerability from climate change and population growth. *Science*, **289(5477)**, 284-288.
- Vörösmarty, C.J., P.B. McIntyre, M.O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S.E. Bunn, C.A. Sullivan, C.R. Liermann, and P.M. Davies, 2010:** Global threats to human water security and river biodiversity. *Nature*, **467(7315)**, 555-561.
- Wada, Y., D. Wisser, S. Eisner, M. Flörke, D. Gerten, I. Haddeland, N. Hanasaki, Y. Masaki, F.T. Portmann, T. Stacke, Z. Tessler, and J. Schewe, 2013:** Multi-model projections and uncertainties of irrigation water demand under climate change. *Geophysical Research Letters*, **40(17)**, 4626-4632.
- Walling, D.E., 2009:** *The Impact of Global Change on Erosion and Sediment Transport by Rivers: Current Progress and Future Challenges*. The United Nations World Water Assessment Programme (WWAP), Scientific Paper, United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France, 26 pp.
- Wang, A., D.P. Lettenmaier, and J. Sheffield, 2011:** Soil moisture drought in China, 1950-2006. *Journal of Climate*, **24(13)**, 3257-3271.
- Wang, D. and X. Cai, 2010:** Comparative study of climate and human impacts on seasonal baseflow in urban and agricultural watersheds. *Geophysical Research Letters*, **37**, L06406, doi:10.1029/2009GL041879.
- Wang, H., Z. Yang, Y. Saito, J.P. Liu, X. Sun, and Y. Wang, 2007:** Stepwise decreases of the Huanghe (Yellow River) sediment load (1950-2005): impacts of climate change and human activities. *Global and Planetary Change*, **57(3-4)**, 331-354.
- Wang, J., Sabrina, G. S. A. Rothausen, C. Declan, Z. Lijuan, X. Wei, P.H. Ian, and L. Yumin, 2012:** China's water-energy nexus: greenhouse-gas emissions from groundwater use for agriculture. *Environmental Research Letters*, **7(1)**, 014035, doi:10.1088/1748-9326/7/1/014035.
- Wang, X., J. Zhang, R. He, E. Amgad, E. Sondoss, and M. Shang, 2011:** A strategy to deal with water crisis under climate change for mainstream in the middle reaches of Yellow River. *Mitigation and Adaptation Strategies for Global Change*, **16(5)**, 555-566.
- Ward, P.J., K.M. Strzepek, W.P. Pauw, L.M. Brander, G.A. Hughes, and J.C.J.H. Aerts, 2010:** Partial costs of global climate change adaptation for the supply of raw industrial and municipal water: a methodology and application. *Environmental Research Letters*, **5(4)**, 044011, doi:10.1088/1748-9326/5/4/044011.
- Weatherhead, E.K. and N.J.K. Howden, 2009:** The relationship between land use and surface water resources in the UK. *Land Use Policy*, **26(Suppl 1)**, S243-S250.
- Webb, M.D. and K.W.F. Howard, 2011:** Modeling the transient response of saline intrusion to rising sea-levels. *Ground Water*, **49(4)**, 560-569.
- Weiland, F.C.S., L.P.H. van Beek, J.C.J. Kwadijk, and M.F.P. Bierkens, 2012a:** Global patterns of change in discharge regimes for 2100. *Hydrology and Earth System Sciences*, **16(4)**, 1047-1062.
- Weiland, F.C.S., L.P.H. van Beek, J.C.J. Kwadijk, and M.F.P. Bierkens, 2012b:** On the suitability of GCM runoff fields for river discharge modeling: a case study using model output from HadGEM2 and ECHAM5. *Journal of Hydrometeorology*, **13(1)**, 140-154.
- Werner, A.D., J.D. Ward, L.K. Morgan, C.T. Simmons, N.I. Robinson, and M.D. Teubner, 2012:** Vulnerability indicators of sea water intrusion. *Ground Water*, **50(1)**, 48-58.
- Whitehead, P.G., R.L. Wilby, R.W. Battarbee, M. Kernan, and A.J. Wade, 2009a:** A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal*, **54(1)**, 101-123.
- Whitehead, P.G., A.J. Wade, and D. Butterfield, 2009b:** Potential impacts of climate change on water quality and ecology in six UK Rivers. *Hydrology Research*, **40(2-3)**, 113-122.
- Wilby, R.L., 2010:** Evaluating climate model outputs for hydrological applications. *Hydrological Sciences Journal*, **55(7)**, 1090-1093.
- Wilby, R.L. and K. Vaughan, 2011:** Hallmarks of organisations that are adapting to climate change. *Water and Environment Journal*, **25(2)**, 271-281.
- Wilby, R.L., P.G. Whitehead, A.J. Wade, D. Butterfield, R.J. Davis, and G. Watts, 2006:** Integrated modelling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK. *Journal of Hydrology*, **330(1-2)**, 204-220.

- Wilcock, R., S. Elliott, N. Hudson, S. Parkyn, and J. Quinn, 2008:** Climate change mitigation for agriculture: water quality benefits and costs. *Water Science and Technology*, **58(11)**, 2093-2099.
- Williams, J.G., 2008:** Mitigating the effects of high-head dams on the Columbia River, USA: experience from the trenches. *Hydrobiologia*, **609**, 241-251.
- Wilson, D., H. Hisdal, and D. Lawrence, 2010:** Has streamflow changed in the Nordic countries? – Recent trends and comparisons to hydrological projections. *Journal of Hydrology*, **394(3-4)**, 334-346.
- World Bank, 2007:** *Guidance Note 7: Evaluating Adaptation via Economic Analysis*. Guidance Notes Series, Mainstreaming Adaptation to Climate Change in Agriculture and Natural Resources Management Projects, Climate Change Team Environment Department, World Bank, Washington DC, USA, 18 pp.
- World Bank, 2010:** *Economics of Adaptation to Climate Change: Synthesis Report*. World Bank, Washington DC, USA, 101 pp.
- Wu, L., Y. Wood, P. Jiang, L. Li, G. Pan, J. Lu, A.C. Chang, and H.A. Enloe, 2008:** Carbon sequestration and dynamics of two irrigated agricultural soils in California. *Soil Science Society of America Journal*, **72(3)**, 808-814.
- WUCA, 2010:** *Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning*. Water Utility Climate Alliance (WUCA), San Francisco, CA, USA, 102 pp.
- WWAP, 2009:** *Water in a Changing World*. World Water Development Report 3, World Water Assessment Programme (WWAP), The United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France and Earthscan, London, UK, 429 pp.
- Xie, Z.C., X. Wang, Q.H. Feng, E.S. Kang, Q.Y. Li and L. Cheng, 2006:** Glacial runoff in China: an evaluation and prediction for the future 50 years. *Journal of Glaciology and Geocryology*, **28(4)**, 457-466.
- Xu, H., R.G. Taylor, and Y. Xu, 2011:** Quantifying uncertainty in the impacts of climate change on river discharge in sub-catchments of the Yangtze and Yellow River basins, China. *Hydrology and Earth System Sciences*, **15(1)**, 333-344.
- Yan, X., H. Akiyama, K. Yagi, and H. Akimoto, 2009:** Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. *Global Biogeochemical Cycles*, **23**, GB2002, doi:10.1029/2008GB003299.
- Yang, D., S. Kanae, T. Oki, T. Koike, and K. Musiak, 2003:** Global potential soil erosion with reference to land use and climate changes. *Hydrological Processes*, **17(14)**, 2913-2928.
- Yang, W., J. Andreasson, L.P. Graham, J. Olsson, J. Rosberg, and F. Wetterhall, 2010:** Distribution-based scaling to improve usability of regional climate model projections for hydrological climate change impacts studies. *Hydrology Research*, **41(3-4)**, 211-229.
- Yasunari, T.J., P. Bonasoni, P. Laj, K. Fujita, E. Vuillemoz, A. Marinoni, P. Cristofanelli, R. Duchi, G. Tartari, and K.-M. Lau, 2010:** Estimated impact of black carbon deposition during pre-monsoon season from Nepal Climate Observatory – Pyramid data and snow albedo changes over Himalayan glaciers. *Atmospheric Chemistry and Physics*, **10(14)**, 6603-6615.
- Yeichieli, Y., E. Shalev, S. Wollman, Y. Kiro, and U. Kafri, 2010:** Response of the Mediterranean and Dead Sea coastal aquifers to sea level variations. *Water Resources Research*, **46**, W12550, doi:10.1029/2009WR008708.
- Yoo, S.-H., J.-Y. Choi, S.-H. Lee, Y.-G. Oh, and D.K. Yun, 2013:** Climate change impacts on water storage requirements of an agricultural reservoir considering changes in land use and rice growing season in Korea. *Agricultural Water Management*, **117**, 43-54.
- Yu, X., L. Jiang, L. Li, J. Wang, L. Wang, G. Lei, and J. Pittock, 2009:** Freshwater management and climate change adaptation: experiences from the central Yangtze in China. *Climate and Development*, **1(3)**, 241-248.
- Zacharias, I. and M. Zamparas, 2010:** Mediterranean temporary ponds. A disappearing ecosystem. *Biodiversity and Conservation*, **19(14)**, 3827-3834.
- Zhang, X. and X. Cai, 2013:** Climate change impacts on global agricultural water deficit. *Geophysical Research Letters*, **40(6)**, 1111-1117.
- Zhang, X., F.W. Zwiers, G.C. Hegerl, F.H. Lambert, N.P. Gillett, S. Solomon, P.A. Stott, and T. Nozawa, 2007:** Detection of human influence on twentieth-century precipitation trends. *Nature*, **448(7152)**, 461-465.
- Zhang, Y.K. and K.E. Schilling, 2006:** Increasing streamflow and baseflow in Mississippi River since the 1940s: effect of land use change. *Journal of Hydrology*, **324(1-4)**, 412-422.
- Zhang, Z., Q. Zhang, C. Xu, C. Liu, and T. Jiang, 2009:** Atmospheric moisture budget and floods in the Yangtze River basin, China. *Theoretical and Applied Climatology*, **95(3-4)**, 331-340.
- Ziervogel, G., M. Shale, and M. Du, 2010:** Climate change adaptation in a developing country context: the case of urban water supply in Cape Town. *Climate and Development*, **2(2)**, 94-110.
- Zimmerman, J.K.H., B.H. Letcher, K.H. Nislow, K.A. Lutz, and F.J. Magilligan, 2010:** Determining the effects of dams on subdaily variation in river flows at a whole-basin scale. *River Research and Applications*, **26(10)**, 1246-1260.
- Zwolsman, G., D. Vanham, P. Fleming, C. Davis, A. Lovell, D. Nolasco, O. Thorne, R. de Sutter, B. Fülöp, P. Staufner, and Å. Johannessen, 2010:** *Climate Change and the Water Industry – Practical Responses and Actions*. Perspectives on Water and Climate Change Adaptation Series, Perspective Document No. 10, Paper prepared by the International Water Association (IWA) Specialist Group on Climate Change (CCSG), on behalf of the IWA, International Water Association, The Hague, Netherlands, 16 pp.