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Grand challenges related to assessment of climate change impacts on freshwater resources

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Abstract

The present contribution reviews a suite of grand challenges related to assessment of climate change impacts on freshwater resources. Among them are challenges related to: detection and attribution of changes in observed records, projections for the future, changes in hydrologic extremes (floods and droughts), assessing and reducing uncertainty, and adaptation to change under uncertainty. The global water system is very complex, so that it is difficult to disentangle individual contributions of various factors to changes in freshwater variables at any scale. As for detection and attribution of changes in global river discharge in 20th century, variations in precipitation were the main force. Other major factors were: temperature effects on evapotranspiration, direct effects of rising atmospheric CO_2 concentration on the physiology and abundance of vegetation, and anthropogenic changes in land cover and land use. A general finding regarding possible future trends in the water cycle is that wet regions will likely become wetter and dry regions to become drier in a warming world. Climate-driven hydrologic changes combine with other pressures on water resources, such as population growth, land use change, changes in life styles increasing water demand, and environmental pollution. A grand global challenge is to provide an adequate basis for adaptation decisions that must be made under strong uncertainty, without reliance on precise projections of changes in hydrologic variables.

1 Introduction

Water in the Earth system circulates between different “water stores” by “water fluxes”, thus it takes part in large-scale mass and heat transfer processes between the atmosphere, the ocean, and the land surface (*cf.* Gerten *et al.* 2005, Kundzewicz 2008). The instant state of water stores (e.g. amount of water in the atmosphere, or in the soil, at any given time) and water fluxes (e.g. precipitation – flux of water from the atmosphere to the terrestrial or oceanic surface of the Earth; evapotranspiration – flux from the Earth surface to the atmosphere; or river discharge) have been changing over time. They are influenced by the climate and also influence the climate (Kundzewicz *et al.* 2007, 2008). Hence, human impact on the climate system via intensification of the 'greenhouse' effect significantly affects freshwater resources (Bates *et al.* 2008; Gerten *et al.* 2012). Yet, estimation of volumes of water in different stores, rates of water fluxes between stores, and the interaction with anthropogenic climate change is uncertain.

The present contribution reviews a suite of grand challenges related to assessment of climate change impacts on freshwater resources, which will be addressed in the following sections. It gives an overview of the current status of relevant studies in the global domain, but neither goes it into detail of the mechanisms nor into arguments of specific issues.

2 Drivers of change

Among the drivers of changes in water cycle are both climatic and non-climatic factors. Direct and indirect interference of humans with the global water cycle has reached a degree now perceptible at global scale (Vörösmarty and Sahagian 2000; Harding *et al*. 2011). The global system is very complex, so that it is very difficult to disentangle individual contributions of various factors to changes in freshwater variables at any scale.

2.1 Climatic drivers

As summarized in IPCC (2007a), "warming of the climate system is unequivocal". This is "evident from observations of increases in global average air and ocean temperature, widespread melting of snow and ice, and rising global average sea level". There is increasing evidence that the lower atmosphere is warming at a variety of scales, up to the global scale. The global combined land and ocean temperature data show a warming of about 0.8 °C over the period 1901–2010. In the last decades, global warming has accelerated – reaching 0.5 °C over the period 1979–2010 alone. Foster and Rahmstorf (2011) found consistent global warming trends ranging from 0.014 to 0.018 K yr^{-1} in all five temperature series they examined for 1979–2010. However, the peculiarity of global temperature trends has also been questioned – Cohn and Lins (2005) stipulate that the Earth system is naturally characterized by strong variability and trends.

Other than temperature, changes in global precipitation are not of high confidence (particularly in the first half of the 20th century) largely due to insufficient data for large scales. Precipitation changes have been less regular than the ubiquitous warming, in both spatial and temporal terms. Nonetheless, there is solid evidence of precipitation increases over land in mid- and high latitudes since 1900 to date (Trenberth *et al.* 2007). Probability of heavy precipitation events especially for most extra-tropical regions also increased. However, the precipitation statistics are strongly influenced by inter-annual and inter-decadal variability, and are sometimes inflicted by problems with data homogeneity, particularly concerning snowfall. Observed changes of the timing, intensity, duration and phase of precipitation are often weak and statistically insignificant.

Apart from changes in precipitation, higher temperatures also contribute to changes in the components of the water cycle, particularly evapotranspiration. Jung *et al.* (2010) have shown that global evapotranspiration over land has significantly fluctuated in recent decades, with an increasing trend (possibly related to global warming) interrupted by regional soil moisture limitation. Also the sea level has been rising over many last decades, in conjunction with the warming, by thermal expansion resulting from temperature rise and melting processes in the cryosphere. Sea level rise has a widespread impact on freshwater resources (e.g., via saltwater intrusion into groundwater and estuaries). Its global average rate from 1993 to 2003, measured by satellites, is 3.1 ± 0.7 mm year^{-1} (IPCC 2007a).

2.2 Non-climatic drivers

In addition to climatic influences, the freshwater resources and water fluxes have been controlled by direct anthropogenic drivers corresponding to population changes and economic development. Many river basins experience massive manipulations of both land and freshwater resources (e.g. in support of humans to provide shelter, food, fiber, fodder and fuel, *cf.* Hoekstra and Mekonnen (2012)). There have been changes in land use practices and in land cover, resulting from urbanization, deforestation or afforestation, intensification or extensification of agriculture, mining, and compression of soil layers. Furthermore, humans attempt to smoothen the spatial-temporal variability of river flow. Regulating river flow in time has been achieved by storage reservoirs (capturing water when abundant and releasing it in times of scarcity), while regulating flow in space has been achieved via water transfer schemes. As a result of dam and reservoir building and operation, the runoff regime of many rivers has been considerably different from the “natural” situation (Kundzewicz 2008; Biemans *et al.* 2011).

Irrigation is by far the most important water use, being responsible for about 70% of global water withdrawal and over 90% of consumptive water use. The global irrigated area (about 19% of global agricultural land) has been increasing at a rate of approximately 2% per annum (cf. Siebert and Döll 2010).

Non-climatic drivers strongly affect water quality as well. In pre-"anthropocene" times, water quality was related to the natural composition of water (and its salinity in particular). Now, changes in pollutant emissions that echo developments in wastewater treatment, changes in land use and management, environmental regulations, and changes in environmental awareness do affect water quality.

Time intervals between human actions and water-related impacts can be significant, further confounding the attribution. Some land use change impacts (e.g. effects of afforestation on low flow, or on nitrate pollution of groundwater) may be revealed only after decades.

The rise in exposure to floods has been caused by human encroachment into floodplains, facilitated by technology and economic imperative that helped populate more flood-prone areas. Many past decisions on land use are now judged wrong as they increase exposure to and damage from floods. Assets at risk from flooding are very high, and still growing (Kundzewicz 2012).

3 Detection of changes in streamflow and climate change track

Streamflow generation – a process in the hydrologic cycle of particular importance for human societies that rely on "blue" freshwater resources – integrates influences of many climatic and non-climatic factors. Variations in streamflow reflect variations in atmospheric conditions – primarily, changes in precipitation (volume, timing, and phase) and changes in evapotranspiration (dependent on atmospheric CO_2 concentration, temperature, energy availability, atmospheric humidity, and wind speed); changes in land use (catchment storage, rate of impermeable area, forested, and agricultural land); and more direct human regulations of the water cycle (dike and dam building, irrigation and drainage, etc.), as reported e.g. by Zhang and Schilling (2006) for the Mississippi river basin and by Gerten *et al.* (2008) for the global scale.

Significant trends in some regional indicators of streamflow have been identified, e.g. a broadly coherent pattern of change in annual streamflow in the study by Milly *et al.* (2005), but no globally homogeneous trend has been reported.

Search for a climate change track in global river flow data (a "hydrologic Mauna Loa", as put by Vörösmarty (2002)) has not been successful yet and the signal-to-noise ratio is low. Not all recent, comprehensive analyses support the observation that streamflow has increased globally during the 20th century. Data and models still cannot provide a clear response to the question whether there is an upward trend in global streamflow (Legates *et al*. 2005; Peel and McMahon 2006; Gerten *et al*. 2008; Dai *et al*. 2009). There is now satellite-based evidence for such an increase as attributable mainly to increased ocean evaporation, but total river discharge amounts and trends derived from such data products also differ much depending on the underlying method (Syed *et al*. 2010 and their Supplementary Information). Interestingly, a global trend in land evapotranspiration – which was positive up to 1997 and then leveled off, possibly due to soil moisture limitation in large parts of the southern hemisphere (Jung *et al*. 2010) – challenges the hypothesis that river discharge is currently increasing and the hydrologic cycle accelerating (see below). The hitherto relatively weak climate change signal is superimposed on a large natural variability of rainfall and river flow (under a confounding effect of land use change). According to Wilby *et al.* (2008), in some basins, statistically significant trends in river flow are unlikely to be found for several decades more.

A robust finding though is that warming leads to changes in the seasonality of river flows in river basins where much winter precipitation still falls as snow, with spring flows decreasing because of trends towards reduced or earlier snowmelt, and winter flows increasing (snowmelt may contribute to winter rather than spring flow), with likely consequences to flood risk (Kundzewicz 2012).

Water quality is clearly influenced by the increase of water temperatures in response to higher air temperatures, which drives the reaction kinetics of key chemical processes, accelerating nutrients' cycling. Moreover, increasing water temperature can contribute to a decrease of dissolved oxygen concentration, adversely affecting the self-purification capacity of water bodies. Effects of increasing water temperature on river biology, e.g. on species numbers (Xenopoulos *et al.* 2005), and on energy supply (van Vliet *et al.* 2012), can also be significant.

4 Attribution of changes in streamflow

Many references aim to attribute the changes in global streamflow and its regional pattern (cf. Gerten *et al*. 2008, 2012). Variations and trends in atmospheric conditions have often been identified as the primary drivers of change in global river discharge. This specifically refers to changes in precipitation (e.g. Déry and Wood 2005; Milly *et al*. 2005; Piao *et al*. 2007; Gerten *et al*. 2008), atmospheric CO_2 concentration and/or temperature (Gedney *et al*. 2006; Krakauer and Fung 2008), and net radiation (Wild *et al*. 2005).

Labat *et al.* (2004) claimed a 4% increase in global total runoff per 1 °C rise in global mean temperature during the twentieth century, but this finding has been challenged (Legates *et al.* 2005; Huntington 2008). Gedney *et al.* (2006) attributed a recently observed rise in global river flow primarily to plant physiological effects (CO_2–induced higher efficiency of plant water use and reduction in plant evapotranspiration) offset by a climate change (precipitation, temperature) signal. However, this attribution has later been challenged. A more complete account of CO_2 effects on plants requires quantification of both physiological and structural vegetation dynamics, net effects of which on evapotranspiration and streamflow may cancel each other out at global scale (Betts *et al*. 1997; Piao *et al*. 2007; Gerten *et al*. 2008).

Large-scale changes in streamflow are also influenced by irrigation and dam construction (Milliman *et al.* 2008; Biemans *et al*. 2011), which potentially affect regional water cycles between land and atmosphere (e.g. Shibuo *et al*. 2007; Lucas-Picher *et al*. 2011). The type of vegetation, e.g. whether broad-leaved or needle-leaved, also affects evapotranspiration and runoff patterns (Peel *et al*. 2004). Modeling studies by Piao *et al.* (2007) and Gerten *et al.* (2008) conclude that historic land use changes have strongly affected global river discharge, due to pronounced impacts in regions where these changes have been prominent in the past century. These findings are discussed in more detail in the following.

4.1 Attribution of changes in 20th century global streamflow

Gerten *et al.* (2008) carried out a model-based study that attributed changes in global streamflow between 1901 and 2002, using the LPJmL dynamic global vegetation and water balance model (Bondeau *et al*. 2007; Rost *et al*. 2008). LPJmL computes the temporal dynamics of nine natural plant functional types and twelve crop functional types. It also explicitly considers the partly compensating effects of CO_2 on plants (Leipprand and Gerten 2006): the physiological effect (reduced stomatal aperture, thus reduced leaf-level transpiration due to increased water use efficiency), and the structural effect (enhanced biomass production and/or spreading of vegetation, thus increased regional-scale evapotranspiration). Since cropland and irrigation are also considered in the model, the effects of land use changes and expanding irrigation areas could be quantified. Monthly climate data were taken from the CRU TS2.1 database (Mitchell and Jones, 2005). In addition to a baseline run in which all potential drivers of streamflow – precipitation, temperature, CO_2 concentration, land use, irrigation – were varied over time, simulations were conducted in which only one of the crucial input variables to the model was varied (*ceteris paribus*, i.e. with others held constant at their 1901 level (climate: 1901–1930 average level)), in order to determine the isolated effect of these factors. Changes in annual discharge were then analyzed as shifts between the averages for two time intervals: 1901–1970 and 1971–2002.

4.1.1 Effect of precipitation (baseline vs. precipitation-only simulations)

For many regions, significant shifts in discharge were found between 1901–1970 and 1971–2002, with a pronounced spatial pattern showing either positive or negative shifts even in neighboring regions (Gerten *et al.* 2008). Simulated regional patterns of change – e.g. a widespread decrease in North and West Africa, Central and East Europe and parts of South Asia, and an increase in Siberia, western Australia and parts of South America – largely comply with observations (Milly *et al*. 2005; Piao *et al*. 2007; Krakauer and Fung 2008; Milliman *et al*. 2008).

Global streamflow was simulated to increase between the two periods by about 1,200 km^3 a^{-1} (3%) and exhibited a non-monotonous trend of about 31 km^3 a^{-2} over 1901–2002 (Fig. 1), related primarily to concurrent changes in precipitation. Global precipitation over land itself showed an upward trend in the order of 2.5% over 1901–2002, but the trend was complex, both temporally and spatially. There was an overall increase of global precipitation until the 1950s, then a decrease and another increase in the 1960s/1970s, a decline from the 1970s until the early 1990s and a recovery afterwards (Trenberth *et al.* 2007). The sign and the magnitude of streamflow trends indeed strongly depend on the time window under study. However, the global change was made up of regional anomalies of opposite sign. Precipitation over land increased over the 20th century between 30°N and 85°N. In a band from 10°N to 30°N, precipitation increased markedly before the 1950s, but declined after the 1970s.

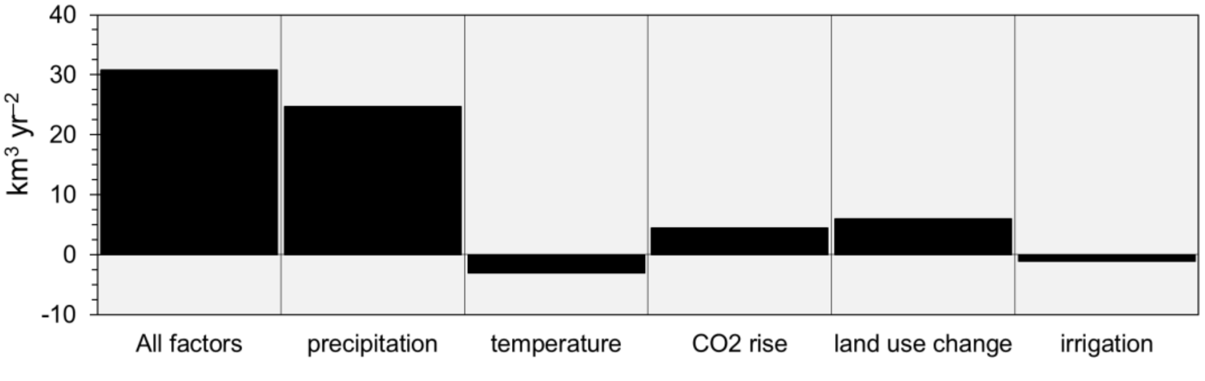


Fig. 1. Trends over the period 1901 to 2002 in global streamflow and individual contributions of different drivers, simulated by the LPJmL global hydrology and vegetation model, based on results from Gerten *et al.*

(2008).

4.1.2 *Effect of temperature*

The isolated temperature impact usually was a decrease in streamflow, due to higher summer evapotranspiration that went along with warmer conditions. This effect was simulated to be most pronounced at high latitudes and in parts of Central Asia (Gerten *et al.* 2008). While temperature had a clearly weaker effect than precipitation, its global signature became increasingly evident in recent decades in the model simulations. Locally and regionally, the effect of temperature on river flow can be very important. For example, it was clearly observed in Switzerland during the hot and dry summer of 2003 that extensive melting of glaciers contributed a large portion of river flow.

4.1.3 *Effect of CO_2 rise*

Rising atmospheric concentration of CO_2 can explain simulated decreases in streamflow in some semiarid regions, indicating higher transpiration due to expanding vegetation and higher net primary production (Gerten *et al.*, 2008). In contrast, higher discharge in response to CO_2 rise in parts of the Northern Hemisphere suggests a dominance of the physiological CO_2 effect that reduces plant transpiration. Globally, the net result of physiological and structural responses on discharge was a small increase, which – though smaller in magnitude – supports conclusion of Gedney *et al.* (2006) that the rise in atmospheric concentration of CO_2 increased global river discharge. Note that those authors considered only the physiological CO_2 effect, without taking into account the simultaneous increase in vegetation productivity and abundance accounted for in such models as LPJmL. Results by Gerten *et al.* (2008) are in line with numerous laboratory and field experiments that suggest a net decline in plant transpiration if ambient CO_2 concentration is increased (see e.g. Leipprand and Gerten 2006; de Boer *et al.* 2011).

4.1.4 *Effect of land-cover change and land use change*

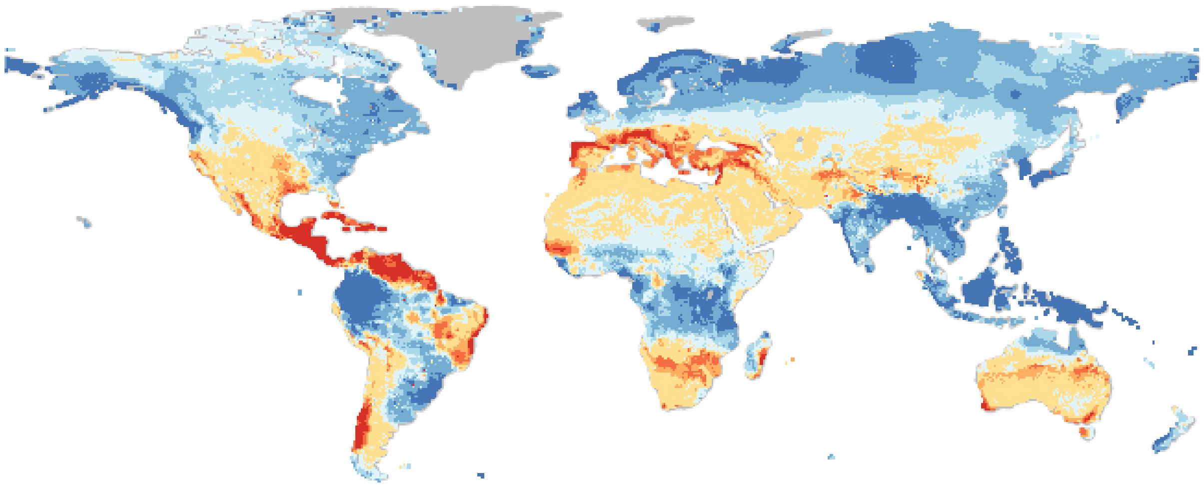
Simulations in which only land use was varied according to historical trends indicated an increase in streamflow by about 6 km^3 yr^{-1} (1.6%), which can be traced back to regions where widespread land cover changes have occurred in the past. This agrees with observational evidence that deforestation implies shorter growing periods, lower rooting depths and lower interception losses. These processes all tend to increase average streamflow at the regional scale. For example, LPJmL modeled an increase in eastern Brazil in response to deforestation, as is also reflected in observations (Piao *et al*. 2007). The results are in line with those by Piao *et al*. (2007), suggesting that land cover changes were the second important factor contributing to changes in global discharge over the past century.

4.1.5 Effect of irrigation

Albeit regionally growing in the second half of the 20th century, the global effect of irrigation on discharge was found to be small in the LPJmL simulations by Gerten *et al.* (2008), *cf.* Fig. 1. This is because only a relatively small fraction of global cropland is being irrigated; and because contrasting effects of irrigation and land-use change have largely cancelled each other out globally (see also Gordon *et al*. 2005).

5 Projections for the future

Model-based temperature projections agree on the sign of ubiquitous warming (cf. IPCC 2007a). Climate projections show also increases in globally averaged mean water vapor and precipitation over the 21st century. However, projections of future precipitation are considerably less clear and more uncertain. A general finding is that wet regions will likely become wetter and dry regions will become drier in the warming world. By the 2050s, annual average river flow and freshwater availability are projected to decrease by 10–30% over some dry regions at mid-latitudes and in the tropics, while increasing by 10–40% at high latitudes and in some wet tropical areas (Milly *et al*. 2005). Even more pronounced changes are likely by the end of the present century (Kundzewicz *et al*. 2007, 2008). More recent projections are illustrated in Fig. 2.



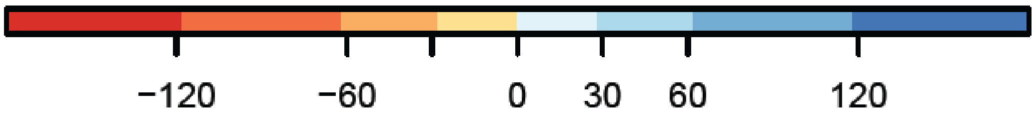


Fig. 2. Changes in runoff (in mm; 2071-2100 vs. 1971-2000) simulated by the LPJmL global vegetation and hydrology model. Shown is the ensemble average change given climate change projections from 18 GCMs pattern-scaled for the IPCC's RCP8.5 scenario (after Gerten, D., Schaphoff, S., Rastgooy, J., Deryng, D., Wallace, C. Warren, R., and Edwards, N. *Crop and Water Impacts*, ERMITAGE project deliverable, May 2012).

A shift in part of winter precipitation from snow to rain, projected as a consequence of temperatures rise, will lead to a change in the timing of the peaks of streamflow in many continental and mountain regions. The spring snowmelt peak is projected to come earlier (possibly in winter). As glaciers will retreat due to warming, river flows will increase in the short term ("meltwater dividend") but will decline when glaciers disappear. More than one billion people (nearly one seventh of the world population) live in river basins supplied by melt water (glacier-melt or snowmelt) from major mountain ranges, such as the Himalayas, the Hindukush and the Andes (Barnett *et al*. 2005; Vergara *et al*. 2007), and changes in the timing of streamflow in these areas (e.g. reduction of low flows in summer and autumn) may have large impacts on freshwater availability.

The beneficial impacts of projected increases in annual runoff in areas such as (south)eastern Asia are likely to be tempered by adverse impacts of increased variability and seasonal runoff shifts on water supply and flood risk, in particular in heavily populated low-lying river deltas (Kundzewicz *et al*. 2007). Furthermore, additional precipitation during the wet season in those regions may not alleviate dry-season problems if there is no capacity in place to store the extra water. Areas in which runoff is projected to decline are likely to face a reduction in the value of the services provided by freshwater resources, e.g. as habitat for freshwater fauna and flora (Barnett *et al*. 2005), or as energy source (Lehner *et al*. 2006).

One-quarter of the global population live in coastal regions that have less than 10% of the global renewable water supply and are undergoing rapid population growth. Saline intrusion into groundwater due to excessive water withdrawals from aquifers is expected to be exacerbated by the effect of sea level rise, leading to reduction of freshwater availability (Kundzewicz *et al*. 2007, 2008). There is an amplification effect as even a small sea level rise may induce very large decreases in the thickness of the freshwater lens below small islands.

Potential changes in the volume, timing and quality of surface water and groundwater will impact, to varying degrees, on the reliability of safe water supplies, on exposure to damaging floods and droughts, on the availability of water for industrial and cooling purposes, on water-borne transport, water-related diseases and, of course, on aquatic ecosystems and the many services they provide. As an indication of the potential extent of the impact of changes in freshwater availability, global-scale studies (Arnell 2004; Alcamo *et al*. 2007) suggest that many millions of people living in water-stressed areas will be adversely affected by climate change and severity of impacts would partly depend on adaptation to change. Alcamo *et al.* (2007) show that the areas where water stress is projected to increase are 2-4 times larger than the areas where water stress is projected to decrease.

An important challenge related to global and regional climate and freshwater projections reads: how would different levels of warming (e.g. under different climate policies) impact freshwater systems? Gerten *et al.* (2013) provide global maps of the warming level that induces critical impacts on regional freshwater supply and also ecosystems. Results suggest that even the 2°C warming would not prevent higher water stress in some, mainly subtropical, regions. More regions are simulated to be affected only at higher warming levels, with lower intensity, or with higher uncertainty. According to the analysis by Gerten *et al.* (2013), if the average global warming reaches 2°C, 3.5°C and 5°C above the preindustrial level, the portion of the world population exposed to stronger or new water stress would reach, respectively, 8%, 11% and 13%.

6 Changes in hydrologic extremes

Observed and projected changes in precipitation and especially in hydrologic extremes are generally less coherent than those observed for temperature, with inconsistencies between studies, regions and/or seasons. Characteristics of water-related extremes – droughts, intense precipitation, and floods – have been changing with time, but the causes and patterns of these changes are complex.

Droughts may have become more widespread, more intense and longer in many regions around the globe, due to reduced land precipitation and/or warming that enhances evapotranspiration and drying. Dai *et al.* (2004) showed that very dry areas (defined as land areas with the value of Palmer Drought Severity Index, PDSI ≤ -3.0) more than doubled, globally, from approx. 12% to 30% since the 1970s. Trends in the PDSI proxy were found to be largely affected by changes in temperature, not precipitation. However, results of a search for trends in hydrologic drought for over 600 streamflow records in Europe, carried out by Hisdal *et al.* (2001), did not support the general hypothesis of increasing severity or frequency of drought conditions. Also Svensson *et al.* (2005) did not detect ubiquitous decrease in low flows. Based on soil moisture simulations with an observation-driven land surface model for the time period 1950-2000, Sheffield and Wood (2008a) found trends in drought duration, intensity, and severity predominantly decreasing, but with strong regional variation and including increases in some regions. More recently, Dai (2011) updated the record used earlier (Dai *et al.* 2004) and found widespread increases in drought both based on various versions of PDSI (for 1950-2008) and soil moisture output from a land surface model (for 1948-2004). Seneviratne *et al.* (2012) asserted that there are still large uncertainties regarding observed large-scale trends in droughts. Studies do not agree on the sign of the global trend.

Drought projections for the 2090s made by Burke *et al.* (2006) show a net overall global drying trend. Globally by the 2090s, the drought-affected land surface is projected to increase in extent, while the proportion of the land surface in extreme drought at any one time is predicted to increase ten-fold from the present. The number of extreme drought events per 100 years and mean drought duration are projected to increase by factors of two and six, respectively, by the 2090s. The overall drying trend is projected with a decrease in global average value of the Palmer Drought Severity Index throughout the 21st century (Burke *et al.* 2006). Burke and Brown (2008) undertook a global analysis of projected changes and found a statistically significant increase of the land surface in drought for three out of four indices considered.

The frequency, distribution, and intensity of heavy precipitation is not adequately simulated by the present generation of global climate models. Evaluation is further hampered by incomplete data on the historical information related to frequency and severity of extremes. However, changes in precipitation extremes are consistent with the warming. Analyses of land areas with sufficient data indicate increases in heavy precipitation events in recent decades, even if results vary between regions and seasons. Existing climate models, by necessity designed for larger scales, are often poor at reproducing local climate extremes, due to, *inter alia*, inadequate (coarse) resolution. Since many extreme events, such as those associated with intense precipitation, occur at smaller temporal and spatial scales, where climate simulation skill is currently limited and local conditions are highly variable, projections of future changes cannot be made with a high level of confidence. Nevertheless, Seneviratne *et al.* (2012) assessed that there is medium confidence that anthropogenic influence has contributed to changes in extreme precipitation at the global scale.

Destructive floods observed all over the world have led to record-high material damage. The costs of extreme weather events have exhibited a rapid upward trend, and yearly economic losses from large flood events have increased by an order of magnitude between the 1950s and 1990s in inflation-adjusted dollars. Disaster losses have grown more rapidly than population or economic growth, possibly suggesting a climate change contribution (Mills 2005). However, increases in flood damage can still be primarily attributed to non-climatic factors, such as increase in exposure and vulnerability (Handmer *et al.* 2012, Kundzewicz *et al.* 2013).

Kundzewicz *et al.* (2005, 2007) found no general global trend in the incidence of floods. Seneviratne *et al.* (2012) assessed that there was low agreement and thus low confidence at the global scale regarding the change in magnitude or frequency of floods or even the sign of changes.

Seneviratne *et al.* (2012) assessed that the frequency of heavy precipitation or the proportion of total rainfall from intense events will likely increase in the 21st century over many areas of the globe, in particular in high latitudes and tropical regions, and in winter in the northern mid-latitudes. They displayed projected changes in return periods of annual maximum daily precipitation. In general, extreme precipitation is expected to become more extreme, but projected changes are region-specific, with larger changes at high latitudes and in tropical regions, and overall larger uncertainty in drier regions. Seneviratne *et al.* (2012) further concluded that there is medium confidence (based on physical reasoning) that projected increases in heavy rainfall would contribute to increases in local flooding and thus these regional variations in projections of changes in heavy precipitation play an important role for resulting assessments of potential changes in flood occurrence at the regional scale.

Hirabayashi *et al.* (2008) examined projections of return periods of floods and droughts, worldwide, producing global maps of changes, indicating areas where rare floods are expected to become more common.

Over large areas, hydrologic extremes, floods and droughts, may become more extreme (more frequent and more severe) in the warming climate, affecting water quality. Increase in intense precipitation affects the rate at which pollutants are flushed to rivers and overloaded storm sewer and wastewater systems may become sources of water pollution. Water quality problems during droughts can be severe as well, since decrease in flow volumes adversely affects dilution of nutrient and pollutant loads.

7 Uncertainty

Among the grand challenges – burning research needs – are those that may lead to reducing uncertainty in understanding, observations, and projections of climate change, its impacts, and vulnerabilities. We have to improve understanding of how climate change might affect freshwater in order to better assist water resources planners who adapt to change. However, the imperative that uncertainties have to be reduced has been discussed for a very long time and indeed major, highly funded, research efforts have been generated. Yet, uncertainties in projections of future changes have actually grown, even if characterization of uncertainty has improved – i.e. unknown unknowns turned into known unknowns. Trenberth (2010) phrased it as: "More knowledge, less certainty". We know increasingly well that we do not know well enough.

There is astonishing uncertainty regarding the volumes of observed streamflow and other components of the water cycle at the global scale. As phrased by John C. Rodda (pers. comm.), we are "guessing rather than assessing" global freshwater resources. Existing assessments of precipitation (*cf.* Biemans *et al.* 2009) and river flow (*cf.* Shiklomanov and Rodda, 2003) do largely differ, since the data base is insufficient and some areas are neither densely nor permanently gauged. Recent estimates – averages for the period 1985 to 1999 derived from eleven global hydrology and land surface models forced by the same climate dataset – suggest that global annual discharge ranges from 42,000 to 66,000 km^3 yr^{-1} (Haddeland *et al*. 2011). While a part of this large uncertainty range can be attributed to the different representations of crucial hydrologic processes in different models – which suggests a major challenge for hydrologic and climate impacts modeling alike (Schewe *et al.* 2013) – poor knowledge of the amount (and detailed spatio-temporal distribution) of precipitation over the runoff-generating areas is the prime source of uncertainty.

If only short hydrometric records are available, the full extent of natural variability can be understated and detection studies confounded. Data on water use, water quality, groundwater, sediment transport, and also aquatic ecosystems are even less available. Climate change impacts on these processes (not only via temperature, but also altered flow regimes, water level, and ice cover) are not adequately understood. On the modeling side, better integration of climate change modeling and impact modeling is needed and this requires solving a range of difficult problems related to scale mismatch between models (large grid cells in climate models *vs.* much smaller grid cells in hydrologic models) and treatment of uncertainty.

Progress in understanding is conditioned by adequate availability of observation data, which calls for enhancement of monitoring endeavors worldwide and reversing the tendency of shrinking observation networks for economic reasons. The lack of information is notorious, and critical, in developing countries.

An example of data-related difficulties is the continental runoff study by Gedney *et al.* (2006) and related discussion (Peel and McMahon 2006) challenging the representativeness of the dataset and the practice of runoff reconstruction. Adequate data base is crucial to understanding observed changes and to improve models, which can then be used for more trustworthy future projections. On top of the uncertainties in climatic conditions, it remains a challenge to attribute observed or simulated changes in freshwater resources to the drivers that may have caused these changes, which is confounded by existing large uncertainties in the anthropogenic driving forces. This renders it necessary that the hydrologic sciences become increasingly interdisciplinary (Wagener *et al.* 2010).

There are many sources of uncertainty in projections of the future water cycle. These uncertainties are associated with the internal variability of the climate system; external forcing (for example increased concentrations of greenhouse gases – dependent on socio-economic development and effectiveness of climate change mitigation, solar and volcanic influences, and changes of land use); climate model sensitivity; impact (hydrologic) model performance; and adaptation. The initial uncertainty, related to future social and economic development, is considerably amplified along this chain; for the same emission scenario, different models produce different impacts. This difference is often larger than that arising in one model with different emission scenarios. For example, for precipitation changes until the end of the 21st century, the multi-model ensemble mean exceeds the inter-model standard deviation only at high latitudes (Kundzewicz *et al.* 2007). Uncertainties in climate change projections increase with the length of the time horizon. In the near term, climate model uncertainties may play a more important role; while over longer time horizons, uncertainties due to the selection of emissions scenario become increasingly significant.

Uncertainty can be illustrated by the fact that precipitation, the principal input signal to freshwater systems, is not adequately simulated in present climate models. The models cannot reconstruct the recorded precipitation in the instrumental observation period with satisfactory accuracy, hence require a bias correction before simulating future conditions (Hagemann *et al.* 2011). There is also a strong inter-model uncertainty – over large areas, climate models disagree as to the direction of change of future precipitation. Consequently, quantitative projections of changes in streamflow at the basin scale, relevant to water management, remain largely uncertain in many regions. In high latitudes and parts of the tropics, though, climate models are consistent in projecting future precipitation increase, while in some subtropical and lower mid-latitude regions, they are consistent in projecting precipitation decrease (Milly *et al.* 2008; Knutti and

Sedláček 2012; also see Fig. 2). Between these areas of robust increase and decrease in model projections, there are areas with high uncertainty, where the current generation of climate models do not agree on the sign of precipitation and runoff changes. Hence, impact assessments based on only one or a few model scenarios may yield contrasting river flow projections, so that a new framework for handling uncertainty is needed to support the process of decision making. Wilby and Harris (2006) show how components of uncertainty can be weighted, leading to conditional probabilities for future impact assessments.

As global climate models (GCMs) continue to be developed, with increasing spatial resolution and better parameterizations of smaller-scale processes that cannot be fully resolved in the models, e.g., relating to land cover, topography, clouds, they could become increasingly useful for investigating local features of the water cycle (Seneviratne *et al.* 2012). Uncertainty is also related to a transfer from larger to smaller scale – aided by statistical and dynamical downscaling methods (though constrained by the reliability of boundary conditions from GCMs).

Traditionally, but incorrectly, measure of uncertainty has been equated with the range of projections, and confidence was assessed through simple quantification of the number of models that show agreement in the sign of a specific climate change. It was assumed that the greater the number of models in agreement, the greater the robustness, but this stance has shortcomings. Models may agree on a projected direction of change, but perhaps they are all wrong. If the change is controlled by processes that are not well understood and validated in the present climate, there can be large errors in the projections, no matter how good the model agreement may be. Possible common biases among models are usually not accounted for, and, by nature, they cannot.

An important challenge is related to hydrologic model intercomparison (Haddeland *et al.* 2011; Schewe *et al.* 2013), and to determination of appropriate metrics for weighting models (can we trust projections by models that perform poorly for the past observation data?). Uncertainties can be explored, and quantification can be attempted, through the combined use of observations and re-analyses, process understanding, a hierarchy of climate models, and ensemble simulations, be it multi-model ensembles, intra-model ensembles, and ensembles generated by perturbed and stochastic physics (Seneviratne *et al.* 2012). However, there are inherent, possibly irreducible, uncertainties of the climate system, so that a shift of emphasis from “reduce uncertainties” to “risk reduction” tends to be necessary. The implied issue is: how to make rational decisions in water resources planning and design, without being able to know the future with adequate precision

(Kundzewicz *et al.* 2007, 2008)?

8 Adaptation

It has been conveniently assumed that the natural freshwater resource base is constant, and hydrologic design rules have been based on the assumption of stationary hydrology, tantamount to the principle that the past is the key to the future. Now, the validity of this principle is challenged (Kundzewicz *et al*. 2007; 2008; Milly *et al.* 2008). Yet, adequate tools for non-stationary systems are not in place yet. The stake is high, as annual global investments in water infrastructure easily reach hundreds of billions of US$.

It is necessary to evaluate social and economic costs and benefits (in the sense of avoided damage) of adaptation, at several time scales. However, since uncertainty of projections is high, climate models with bias reduction and downscaling methodologies are not ready for prime time yet (Kundzewicz and Stakhiv 2010). Downscaling cannot compensate for the basic inadequacies of the climate models. The issue of applicability and credibility of GCM results generated a vigorous scientific debate (cf. Koutsoyiannis *et al.* 2008; 2009; Anagnostopoulos *et al.* 2010; Wilby 2010). Since the range of projected futures is broad, a question: ”adapt to what?” comes about.

A grand global challenge is to provide a better basis for decisions under uncertainty. Improved characterization of uncertainty and incorporating climate change information in risk management framework could help water resources planners in their efforts to adapt to uncertain future changes.

If studies come to predict, in a reliable way, a significant increase in the severity of hydrologic extremes in the changing world, then existing procedures of designing dikes, spillways, dams and reservoirs, polders, by-pass channels, etc., traditionally based on the assumption of stationarity of river flow, would have to be revised. Otherwise, systems would be wrongly conceived, under- or over-designed, resulting in either inadequate performance or excessive costs (Milly *et al.* 2008). In some areas, one would have to undertake long-lasting and costly efforts of redesigning and building higher levees and larger storage volumes, to accommodate larger future flood waves if the same (or higher) safety standards have to be reached.

Necessary adaptation to climate change in the water sector goes beyond structural measures. It also includes forecasting-warning systems, insurance instruments and a plethora of means to improve efficiency of water use (e.g. via demand management). Important are behavioral changes, economic and fiscal instruments, legislation, institutional changes, etc. Agriculture is a critically water-dependent sector, the more so the stronger world population and, thus, global food demand grow. If, for example, climate change brings about decreases in crop yields (mediated by decreasing water availability in rivers, reservoirs or the soil), specific adaptation measures need to be put in place. This portfolio ranges from more effective water use in irrigation – noting that irrigation efficiency is worryingly low in many places (compare Rost et *al.* 2008), more effective water use in rainfed agriculture including water harvesting and soil conservation methods (which may increase global food production substantially, as suggested by Molden *et al.* 2007; Rost *et al.* 2009); and eventually changes in diets (Falkenmark and Lannerstad 2010), in concert with a paradigm shift away from focus on freshwater supply towards demand management. There is no blueprint solution on tackling water scarcity in food production – site-specific combinations of adaptive measures are needed that optimally account for the water-food-energy nexus in multi-purpose systems, ensuring resource use efficiency in these three domains alike (Hoff 2011). Regions without enough water resources to produce desired goods may benefit from international trade. Indeed, virtual water trade is an effective adaptation measure in an increasingly connected, globalized world, which may play an even more prominent role in the future (Hoff 2009).

Uncertainty has implication for adaptation practices (Kundzewicz *et al.* 2007, 2008), as adaptation procedures need to be developed which do not rely on precise projections of changes in hydrologic variables. Furthermore, it is difficult to credibly assess water-related consequences of climate policies and emission pathways. Improved incorporation of projections of current climate variability into water-related management would make adaptation to future climate change easier. Water resources planners in some countries and regions are already explicitly incorporating the potential effects of climate change into policies and specific design guidelines (e.g. on design floods – introduction of safety factors, in absence of crisp numbers delivered by the science).

The monetary costs and benefits of adaptation in freshwater management, including damage avoided, are expected to be large, but are not adequately known (*cf.* Kundzewicz *et al.* 2007). The likelihood of deleterious impacts, as well as the cost and difficulty of adaptation, are expected to increase with magnitude and speed of global climate change (Stern 2006). Hence, effective mitigation of climate change (IPCC 2007b) would help reduce adverse impacts on water systems and resources. However, there is a complex interplay between adaptation to, and mitigation of, climate change. In general, mitigation policies reduce the impacts and need for adaptation to climate change but some mitigation measures (e.g. bioenergy) may constrain adaptation options and even consume freshwater resources that could alternatively be used for crop irrigation or other purposes (Yeh *et al.* 2011). Some potential water management adaptation measures (e.g., pumping of deep groundwater, or water treatment) are very energy-intensive, thus not fulfilling water-food-energy nexus criteria mentioned above. Desalination is energy-intensive, but its costs decrease at a fast pace. Synergies are also possible – enhancing wetlands is beneficial for both mitigation (carbon storage) and adaptation (disturbance control).

Freshwater resources management is clearly linked to other policy areas (e.g. sustainable development, energy projections, nature conservation, disaster risk prevention). Hence there is an opportunity to align adaptation measures across multiple water-dependent sectors. Adaptation to climate change should also include reduction of the multiple non-climate-related pressures on freshwater resources, such as water pollution and increase of water withdrawals, as well as improvement of water supply and sanitation in less developed countries. These win-win measures, providing co-benefits, would reduce the vulnerability to climate change and would be beneficial even if future climate change impacts on freshwater resources at the local scale cannot be precisely known. Climate impact and adaptation science requires an integrated approach (*cf.* Sivakumar 2011) and has to cope with a plethora of challenges, also of social, political, economic, environmental, and communication nature.

9 Concluding remarks

There are a suite of grand challenges related to assessment of climate change impacts on freshwater resources. Among these, we discussed detection and attribution of changes in observed records, projections for the future, changes in hydrologic extremes – floods and droughts, assessing (and reducing) uncertainty, and adaptation under uncertainty. The negative impacts of projected climate change on freshwater resources may outweigh its benefits. Many sectors and systems (e.g. water supply and sanitation, agriculture, energy, human health, settlements, infrastructure, industry, transportation, tourism, insurance, and financial services) are dependent on freshwater resources and their availability, so that changes in hydrologic regimes and water quality due to climate change will have socio-economic impacts as well.

These climate-driven hydrologic changes will combine with other pressures on freshwater resources, such as population growth, land use change, changes in life styles increasing water demand and environmental pollution, which are all about to challenge water management in the future.

Projected non-stationarity of freshwater resources opens a Pandora's box with problems. Constancy of statistical properties allowed water planners to coin a convenient notion of a 100-year flood or a 100-year streamflow drought (i.e. a river discharge, whose probability of exceedance in any given year is 0.01 or 0.99, respectively). In non-stationary situation the notion of 100-year event has to be re-defined, and with it the 'traditional' water management practices.

As far as the grand challenge of detection and attribution of changes in global river discharge is concerned, it can be stated that variations in precipitation were the main force of 20th century inter-decadal variations and trends in global and regional river discharge. Nonetheless, model results also show that temperature effects on evapotranspiration, direct effects of rising atmospheric CO_2 concentration on the physiology and abundance of vegetation, anthropogenic changes in land cover and land use, and water withdrawals for crop irrigation also played an important role in regions where these driving forces were prominent. However, the magnitudes of the individual contributions to changes in freshwater resources are uncertain, since for many regions data on the transient behavior of the driving forces are not available. For instance, estimates of such important driver as tropical deforestation rates differ notably among data products (see e.g. Cramer *et al.* 2004). Hence, another grand challenge is whether and to what extent the direct effects of anthropogenic activities exceeded the effects of changing climate. The jury is still out. Besides, attribution analyses should focus not just on annual discharge totals but also on seasonal dynamics, including attribution of drought and flood occurrences to different drivers.

It was found that human activities are now contributing to global changes not only in temperature but also in precipitation (Zhang *et al.* 2007). This development will probably continue in the future (Bates *et al.* 2008), as will effects of land use change, irrigation and other anthropogenic processes – requiring hydrologic sciences to think in an increasingly interdisciplinary way and to recognize humanity as a key player in the global water cycle.

A grand global challenge is to provide an adequate scientific basis for adaptation decisions that will be made under high uncertainty, without reliance on precise projections of changes in hydrologic variables.

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