RAPID COMMUNICATION

The implications of projected climate change for freshwater resources and their management

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INTRODUCTION

The Fourth Assessment Report of Working Group II of the Intergovernmental Panel on Climate Change (IPCC) critically assessed thousands of recent publications on different aspects of climate change impacts, adaptation and vulnerabilities. The multi-disciplinary and multi-national authorship of the report, and a large pool of experts involved in a three-stage review process, ensured that a wide variety of available information, opinions and hypotheses was assessed. It also enabled the prioritisation of the findings with respect to their importance, likelihood and confidence. This paper, prepared by lead authors of the freshwater chapter in the recent IPCC Report summarises the key findings concerning projections of climate change impacts on fresh-water resources and their management, adaptation and vulnerabilities (Kundzewicz *et al*., 2007).

IMPACTS AND VULNERABILITIES

Changes in the distribution of river flows and groundwater recharge over space and time are determined by changes in temperature, evaporation and, crucially, precipitation (Chiew, 2007). Some climate change impacts on hydrological processes have been observed already (Rosenzweig *et al*., 2007), and further changes are projected. They vary between regions and seasons.

Figure 1 shows examples of water-related vulnerability "hot spots", where climate change impacts on freshwater resources in the decades to come are a threat to the pursuit of sustainable development of the affected regions. The map represents the ensemble mean change in annual runoff, averaged across a number of different climate models (Nohara *et al*., 2006). Runoff is pro-

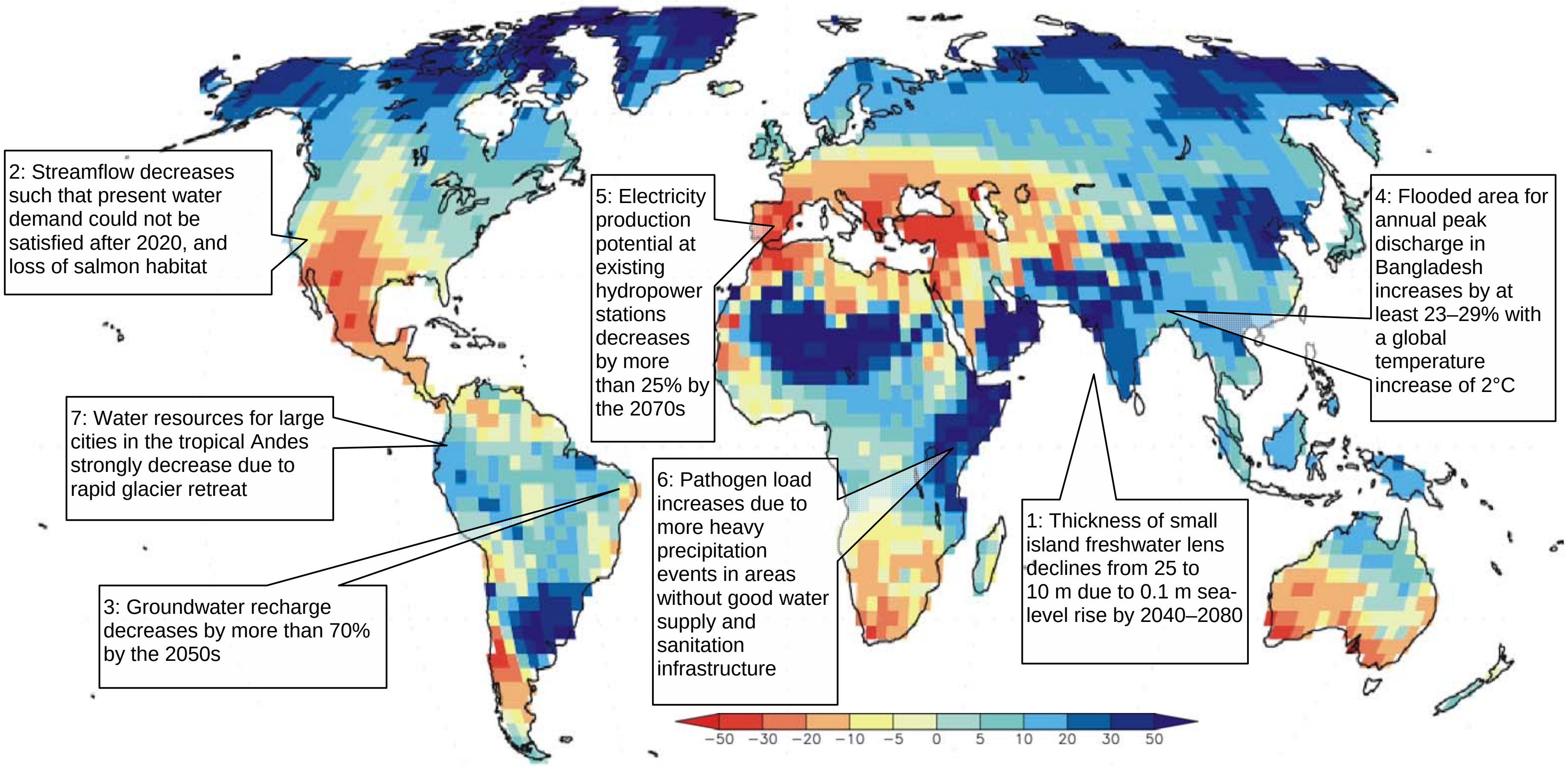

Fig. 1 Illustrative map of future climate change impacts on freshwater which are a threat to the sustainable development of the affected regions (modified after Kundzewicz *et al*., 2007). Background map: ensemble mean change of annual runoff (in percent) between present (1981–2000) and 2081–2100 for the SRES A1B emissions scenario (based on Nohara *et al*., 2006). References in boxes – 1: Bobba *et al*. (2000); 2: Barnett *et al*. (2004); 3: Döll & Flörke (2005); 4: Mirza *et al*. (2003); 5: Lehner *et al*. (2005); 6: Kistemann *et al*. (2002); 7: Vergara *et al*. (2007).

jected to increase in some regions and to decrease in others, exaggerating water resources problems in some catchments and alleviating them in others.

By mid-century, annual average river runoff and water availability are projected to decrease by 10–30% over some dry regions at mid-latitudes and in the dry tropics, while increasing by 10–40% at high latitudes and in some wet tropical areas (Milly *et al*., 2005), and more pronounced changes are likely by the end of this century (Fig. 1). Many of the presently water stressed semi-arid and arid areas are likely to suffer from decreasing water resource availability due to climate change, as both river flows and groundwater recharge decline (cf. Northeast Brazil; Fig. 1 – Box 3; Döll & Flörke, 2005).

A shift in winter precipitation from snow to rain, as temperatures rise, leads to a change in the timing of the peaks of streamflow in many continental and mountain regions. The spring snowmelt peak is brought forward or eliminated entirely, and winter flows increase. As glaciers retreat due to warming, river flows increase in the short term but decline once the glaciers disappear. More than one billion people (one sixth of the world population) live in river basins supplied by meltwater (glacier- or snowmelt) from major mountain ranges, such as the Himalaya, Hindukush and Andes (Barnett *et al*., 2005; Fig. 1 – Box 7; Vergara *et al*., 2007; Magrin *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 resource availability.

Changes in flood and drought frequency and intensity are projected. The proportion of total rainfall from heavy precipitation events is very likely to increase over most areas (IPCC, 2007a); and tropical and high latitude areas are particularly likely to experience increases in both the frequency and intensity of heavy precipitation events. The flood frequency and magnitude is projected to increase in the regions experiencing increase in precipitation intensity, while drought frequency is projected to increase in many regions, in particular those where reduction of precipitation is projected. Globally by the 2090s, drought-affected areas are likely 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 overall drying trend is projected with a decrease in global average value of the Palmer Drought Severity Index of 0.3 and 0.56 per decade, respectively, for the first and the second half of this century (Burke *et al*., 2006). Some drainage basins are projected to experience increase in frequency of both floods and droughts.

The beneficial impacts of projected increases in annual runoff in such areas as eastern and southeastern Asia (Fig. 1), will 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 (Fig. 1 – Box 4; Mirza *et al*., 2003). Furthermore, additional precipitation during the wet season in those regions may not alleviate dry season problems if the extra water cannot be stored. Areas in which runoff is projected to decline are likely to face a reduction in the value of the services provided by water resources, e.g. as habitat for freshwater fauna and flora (Fig. 1 – Box 5; Barnett *et al*., 2004), or as energy source (Fig. 1 – Box 2; Lehner *et al*., 2005).

Few studies have assessed the potential effect of climate change on water quality and most of them refer to developed countries and do not address notable differences in water quality problems between developed and developing countries (Jiménez, 2003). It is clear that an increase in water temperature alters the rate of operation of some key chemical processes in water. Also, changes in intense precipitation events impact the rate at which materials are flushed to rivers and groundwater, and changes in flow volumes affect dilution of loads. Key consequences of declining water quality due to climate change include increasing water withdrawals from low-quality sources; greater pollutant loads from diffuse sources due to heavy precipitation (via higher runoff and infiltration); water infrastructure malfunctioning during floods; and overloading the capacity of water and wastewater treatment plants during extreme rainfall (Fig. 1 – Box 6; Kistemann *et al*., 2002). 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 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). Even a small sea-level rise may induce very large reductions in the thickness of the freshwater lens below small islands (cf. Fig. 1 – Box 1; Bobba *et al.*, 2000).

Taken together, these 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 flood events, on the availability of water for industrial and cooling purposes, on water-borne transport, water-related diseases and, of course, aquatic ecosystems and the services they provide. As an indication of the potential extent of the impact of changes in water availability, global-scale studies (Arnell, 2004; Alcamo *et al.*, 2007) suggest that billions of people living in water-stressed areas will be adversely affected by climate change. The actual numbers impacted, however, will depend partly on how population and climate change, but also on how water managers adapt to changing circumstances. Projections by Alcamo *et al.* (2007) show that, depending on the scenario and climate model, water stress increases (between current conditions and the 2050s) over 62.0–75.8% of the total global river basin area and decreases over 19.7–29.0% of this area.

ADAPTATION

The likelihood of deleterious impacts, as well as the cost and difficulty of adaptation, are expected to increase with magnitude and speed of the global climate change (Stern, 2006). Hence, effective mitigation of climate change (IPCC, 2007c) is necessary to reduce the adverse impacts of climate change on water resources. However, we are already committed (Wigley, 2005) to further warming and corresponding water-related impacts. It is therefore necessary to adapt to changes in the volume, timing and quality of water.

Climate change will affect current water management practices and the operation of existing water infrastructures, which are very likely to be inadequate to overcome the negative impacts of climate change on water supply reliability. Traditionally, it has been conveniently assumed that the natural water resource base is constant, and hydrological 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 limited (Kundzewicz *et al.*, 2007). Therefore, the current procedures for designing water-related infrastructure must be revised. Otherwise, systems will be wrongly conceived, under- or over- designed, resulting in either inadequate performance or excessive costs. For example, water quality systems may need to be re-designed to cope with less self-purification in warmer water with lower oxygen concentration, and increased turbidity may increase significantly the costs and challenges of treating water to potable standards (Miller & Yates, 2006). 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) and related behavioural change, economic and fiscal instruments, legislation, institutional change, etc.

Climate change has introduced large uncertainties into the estimation of future water resources, including flood risks. Uncertainty has two implications for adaptation practices. First, adaptation procedures need to be developed which do not rely on precise projections of changes in river discharge, groundwater, etc. Second, based on the studies done so far, it is difficult to assess water-related consequences of climate policies and emission pathways with high credibility and accuracy. It is also widely recognized that improved incorporation of current climate variability into water-related management would make adaptation to future climate change easier. Water managers in some countries and regions are already considering explicitly how to incorporate the potential effects of climate change into policies and specific design guidelines. For example, measures to cope with the increase of the design discharge for the Rhine in The Netherlands from 15 000 to 16 000 m^3/s must be implemented by 2015, and it is planned to increase the design discharge to 18 000 m^3/s in the longer term due to expected climate change (Klijn *et al.*, 2001).

The monetary cost of adaptation in freshwater management is expected to be large, but it has only been quantified for a few specific aspects and regions (e.g. MacNeil, 2004; Hall *et al.*, 2005).

In addition, there are complex linkages between adaptation and mitigation. Some potential water management adaptation measures (e.g. desalination, pumping of deep groundwater, or water treatment) are very energy-intensive and their implementation would increase greenhouse gas emissions (Mata & Budhooram, 2007). In general, mitigation policies reduce the impacts and need for adaptation to climate change but some mitigation measures (e.g. bio-energy) may constrain adaptation options.

Water resources management is clearly linked to other policy areas (e.g. energy projections, nature conservation). Hence there is an opportunity to align adaptation measures across multiple water-dependent sectors (Holman *et al*., 2005a,b). Adaptation to climate change should also include reduction of the multiple non-climate-related pressures on freshwater resources (such as water pollution and high water withdrawals) as well as improvement of water supply and sanitation in developing countries. These win–win measures 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.

RESEARCH NEEDS—REDUCING *vs* MANAGING UNCERTAINTY

Among the urgent research needs are those that may lead to reducing uncertainty, both to better understand how climate change might affect freshwater and to assist water managers who need to adapt to climate change. However, this is an old plea, and easier said than done. After a call to reduce uncertainty was issued in the IPCC First Assessment Report in 1990, major funds have been spent worldwide on reducing uncertainties in understanding, observations, and projections of climate change, its impacts and vulnerabilities. Meanwhile, uncertainties in projections of future changes remain high, even if characterization of uncertainty has been improved recently (IPCC, 2007a).

Precipitation, the principal input signal to freshwater systems, is not adequately simulated in present climate models. Consequently, quantitative projections of changes in river flow at the basin scale, relevant to water management, remain largely uncertain (Milly *et al*., 2005; Nohara *et al*., 2006). In high latitudes and parts of the tropics, 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. 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 (Milly *et al*., 2005; IPCC 2007a,b; Nohara *et al*., 2006). 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 & Harris (2006) show how components of uncertainty can be weighted, leading to conditional probabilities for future impact assessments.

This suggests that a useful parallel pathway to identification of research needs would be to focus on providing a better basis for decisions that must invariably be made under high uncertainty. For example, improved characterization of uncertainty (joint analysis of ensembles of climate models, cf. IPCC, 2007a) could help water managers in their efforts to adapt to uncertain future hydrological changes. In addition, incorporating that type of climate change information in a risk management approach to water resource planning would be useful.

It is necessary to evaluate social and economic costs and benefits (in the sense of avoided damage) of adaptation, at several time scales.

Estimation, in quantitative terms, of future climate change impacts on freshwater resources and their management, should be improved. Progress in understanding is conditioned by adequate availability of observation data, which calls for enhancement of monitoring endeavours world-wide, addressing the challenges posed by projected climate change to freshwater resources and reversing the tendency of shrinking observation networks. The lack of information is notorious, and critical, in developing countries. A recent example of data-related difficulties is the continental runoff study by Gedney *et al.* (2006) and related discussion (Peel & McMahon, 2006) challenging the representativeness of the data set and the practice of runoff reconstruction. Adequate data are crucial to understanding observed changes and to improve models, which can be used for future projections.

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 water-related systems (e.g. aquatic ecosystems) are even less available. Climate change impacts on groundwater, water quality and aquatic ecosystems (not only via temperature, but also altered flow regimes, water level and ice cover) are not adequately understood. On the modelling side, climate change modelling and impact modelling have to be better integrated and this requires solving a range of difficult problems related to scale mismatch and uncertainty. The effects of CO_2 enrichment on evapotranspiration and, hence, runoff and recharge, remain uncertain, with different representations producing different estimates of impact.

CONCLUDING REMARKS

Freshwater resources are among the systems that are particularly vulnerable to climate change (IPCC, 2007b). Climate change affects the world's freshwater resources—freshwater availability, quality, and the destructive potential of water. Overall, the negative impacts of projected climate change on freshwater resources and related systems, including freshwater ecosystems, are assessed to outweigh its benefits (Kundzewicz *et al*., 2007). 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 water resources and their availability, so that changes in hydrological regimes and water quality due to climate change will have socio-economic impacts.

These climate-driven hydrological changes will combine with other pressures on water resources, such as population growth, land-use change (e.g. urbanization, especially in coastal areas; deforestation), changes in life styles increasing water demand and environmental pollution, to challenge water management in the 21st century.

The assessment of the literature on the implications of climate change for freshwater resources and their management conducted for the IPCC identified some strong and robust conclusions indicating the potential magnitude of impact, and highlighted the most important uncertainties. It also revealed an increasing involvement of water managers in adaptation in a number of countries. The assessment also drew three broader conclusions. First, the impacts of climate change, and the most effective ways of adapting to change, depend very much on local hydrological, economic, social and political conditions, and it is difficult to extrapolate results or conclusions from one catchment to another. Second, climate change is superimposed onto other pressures on water resources. Third, little can currently be said about the implications of climate change for the availability of safe water for the most vulnerable—the rural and urban poor in developing countries.

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