Climate change impacts on river basin and freshwater ecosystems: some observations on challenges and emerging solutions

Avi Ostfeld, Stefano Barchiesi, Matthijs Bonte, Carol R. Collier, Katharine Cross, Geoff Darch, Tracy A. Farrell, Mark Smith, Alan Vicory, Michael Weyand and Julian Wright

ABSTRACT

Despite uncertainty pertaining to methods, assumptions and input data of climate change models, most models point towards a trend of an increasing frequency of flooding and drought events. How these changes reflect water management decisions and what can be done to minimize climate change impacts remains unclear. This paper summarizes and extends the workshop outcomes on 'Climate Change Impacts on Watershed Management: Challenges and Emerging Solutions' held at the IWA World Water Congress and Exhibition, Montréal, 2010, hosted by the IWA Watershed and River Basin Management Specialist Group. The paper discusses climate change impacts on water management of freshwater ecosystems and river basins, and illustrates these with three case studies. It is demonstrated through the case studies that engagement of relevant stakeholders is needed early in the process of building environmental flows and climate change decision-making tools, to result in greater buy-in to decisions made, create new partnerships, and help build stronger water management institutions. New alliances are then created between water managers, policy makers, community members, and scientists. This has been highlighted by the demonstration of the Pangani integrated environmental flow assessment, through the Okavango River Basin case study, and in the more participatory governance approach proposed for the Delaware River Basin.

Key words | climate change, environmental flows, management, modeling, river basin, water resources

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INTRODUCTION

Climate change presents a significant additional challenge to the achievement of sustainable water management around the globe. Water is the primary vector medium through which the impacts of climate change will be felt by societies across the world. Successful water management of especially freshwater ecosystems is therefore the key to successful climate change adaptation.

Freshwater ecosystems cover approximately 12.8 million square kilometers of the planet's surface, which is less than 1% of the surface area. In addition to supporting more than 126,000 freshwater species, they provide valuable services for people, with the concept of ecosystems services as a tool for freshwater management growing rapidly (WWF 2009). Ecosystem services (ES) are defined as the ecological conditions and processes that regulate and provide for human well-being (Daily 1997). The types of service provided by freshwater ecosystems are summarized in Table 1 (see also Farrell *et al.* 2011).

Only 2.5% of the total volume of water on the Earth is considered fresh (defined as less than 0.5 g total dissolved solids/liter), and more than two-thirds of this is locked up in glaciers and permanent snow, with the bulk of the remaining third found in deep groundwater stores. Only 0.3% (104,590 km^2) exists as surface water. It is therefore not surprising that we have witnessed increasing poverty, conflict and wars waged around freshwater accessibility.

Table 1 | Examples of freshwater ecosystem services (from Farrell *et al.* 2011)

	Agricultural lands	Peat swamps	Delta	Estuary	Forest	Wetland	Riparian buffer	Lakes/ rivers	Perennial ice/snow	Urban waters	Aquifers
Provisioning											
Water supply		X	X	X	X	X	X	X	X	X	X
Food	X	X	X	X	X	X	X	X	X	X	
Raw materials	X	X	X	X	X	X	X	X			
Medicinal resources	X	X	X	X	X	X	X	X			
Regulating											
Gas and climate regulation	X	X	X	X	X	X	X	X	X		
Disturbance regulation		X	X		X	X	X	X		X	X
Soil erosion control	X		X		X	X	X	X	X	X	
Water regulation	X	X	X	X	X	X	X	X	X	X	X
Biological control					X	X					
Water quality & waste processing	X	X	X	X	X	X	X	X		X	X
Soil formation	X	X	X	X	X	X		X			
Supporting											
Nutrient cycling	X	X	X	X	X	X	X	X		X	
Biodiversity & habitat	X	X	X	X	X	X	X	X	X	X	
Primary productivity	X	X	X	X	X	X	X	X		X	
Pollination	X		X		X	X	X				
Cultural											
Aesthetic	X	X	X	X	X	X	X	X	X	X	
Recreation & tourism		X	X	X	X	X	X	X		X	
Scientific & educational	X	X	X	X	X	X	X	X	X	X	X
Spiritual & religious	X		X	X	X	X	X	X	X		

Some have hypothesized that we have reached a global tipping point where our usage of freshwater resources and supplies has outstripped the planet's ability to replenish them (Gleick 2009). Other studies have revealed that more than half of our planet's wetlands have been lost, and freshwater biodiversity has declined by 35% from 1970 to 2005, which is a rate that is much higher than that occurring in either the forest or marine biomes (Loh 2008).

Vörösmarty *et al.* (2010) reported that nearly 80% of the world's population is exposed to high levels of water insecurity and that 65% of the habitats associated with continental discharge are moderately to highly threatened by economic growth and development. Water insecurity is driven and defined by a number of key threats that include dam density, river fragmentation, consumptive water loss, human water stress/over-abstraction, agricultural water stress, cropland growth, the increase in impervious surfaces, wetland non-connectivity, increases in invasive species and aquaculture, and increased loadings of organic material and compounds, pesticides, sediment, and nitrogen and phosphorus.

Climate change, coupled with the pressures from a global population projected to grow to 9 billion people by the middle of the century (Ha Estelle *et al.* 2010), will continue to degrade freshwater ecosystems unless immediate action to improve governance and management is undertaken.

Habitat loss and degradation present particular challenges to freshwater species that in many cases cannot relocate, with ecosystems often highly concentrated in relatively restricted areas. In addition freshwater species often serve as excellent indicators of ecosystem functions which underpin ES delivery for people, such as the availability of water of sufficient quality and quantity to meet abstraction needs (Ha Estelle *et al.* 2010).

The 4th report of the Intergovernmental Panel on Climate Change (Bates *et al.* 2008) predicted the following impacts on freshwater resources and ecosystems, ranging from likely to a high degree of confidence in their occurrence based on observational records and climate change projections:

- Global warming is likely to cause large-scale changes in the hydrologic cycle impacting timing, intensity, and duration of water flows (Lehner *et al.* 2006).
- Precipitation and average annual runoff will increase in high latitudes but decrease in some subtropical and lower mid-latitudes, especially in regions currently already dry (Nijssen *et al.* 2001; Neelin *et al.* 2003; Labat *et al.* 2004).
- Increased intensity and variability in precipitation will likely increase risks of flooding and droughts (in many locations suffering extreme poverty such as Bangladesh) (Lehner *et al.* 2006).
- Water supplies from glaciers and snow cover will likely decline, reducing river base flows and increasing peak flows (Nijssen *et al.* 2001). The changes in flow regime can consequently cause changes in water quality (Bonte & Zwolsman 2010).
- Temperature changes will likely affect water quality and some forms of pollution, degrading fish and other species' habitats (Van Vliet *et al.* 2011).
- There is a high confidence that rising water temperatures and related changes in ice cover, total dissolved solids (TDS), oxygen levels and circulation will impact freshwater biological systems (Verbrugge *et al.* 2011).
- It is also very likely that increased global average temperature exceeding 1.5 to 2.5 °C with related atmospheric CO_2 concentrations will create significant changes in ecosystem structure, function and resilience – reducing their ability to withstand and recover from shocks (Scholze *et al.* 2006).
- Ecological interactions and shifts in species' geographical ranges, among other negative consequences for biodiversity and ecosystem goods and services, are also projected (Schröter *et al.* 2005).

All of these impacts are magnified considering the very small amount of freshwater resources available to humankind and other freshwater-dependent species.

The objective of this paper is to discuss climate change impacts on water management of freshwater ecosystems and river basins and outline observations on challenges and emerging solutions. The discussion is based on the outcomes of the workshop hosted by the IWA Watershed and River Basin Management Specialist Group at the IWA World Water Congress and Exhibition, Montréal, 2010. The emerging issues are illustrated with examples from the Pangani River Basin (Tanzania), the Okavango River

Basin (Botswana, Angola and Namibia), and the Delaware River Basin (United States).

CHALLENGES

The flow regime is the key factor shaping and defining habitats in river and surrounding freshwater ecosystems, which in turn determine the composition of species. For example, several aquatic and riparian species have developed life history strategies in response to natural variation in the flow regime such as spawning and recruiting. Altering the flow regime often facilitates invasion of non-native species in rivers. In addition, maintaining natural patterns of connectivity within floodplains is essential to the viability of populations of many riverine species (Bunn & Arthington 2002). The magnitude, frequency, duration, timing, and rate of change of the water flows required to sustain freshwater and estuarine ecosystems and human livelihoods depending on these ecosystems, are commonly referred to as environmental flows (or eflows) (Poff *et al.* 1997; Brisbane Declaration 2007).

Climate change and consumptive uses such as hydropower and irrigation are to various degrees modifying the flow regime in river basins worldwide. As a result, the ES that rivers provide in terms of water, food, biochemicals, pathogen control, fiber, spiritual inspiration, conveyance, and recreation, need to be better controlled. Figure 1 illustrates key relationships between hydrological flow regime, ES, and human well-being. Eventually, the combination of these factors erodes the resilience of ecosystems until they cease to cope with sudden changes (Folke *et al.* 2004; Bond *et al.* 2008).

Whereas environmental flows can serve as an important link between conservation and poverty alleviation, the values of securing freshwater ES are not well reflected in the global policy agenda (Forslund *et al.* 2009). Likewise, the water resources community does not sufficiently acknowledge the ways in which natural biogeochemical processes and diverse communities of aquatic biota regulate freshwater quantity and quality (Arthington *et al.* 2010). Climate change increases the challenge to effectively allocate available water resources for balancing both socio-economic and ecological aspects. For example, dams may be essential to deliver a year-round water supply in regions with reduced summer runoff. On the other hand, storing water in reservoirs will increase evaporation and reduce the overall water availability (Palmer *et al.* 2008) and will also reduce water availability for downstream ecosystems.

While environmental water reallocation is needed to manage low flows, making space for rivers to flood in

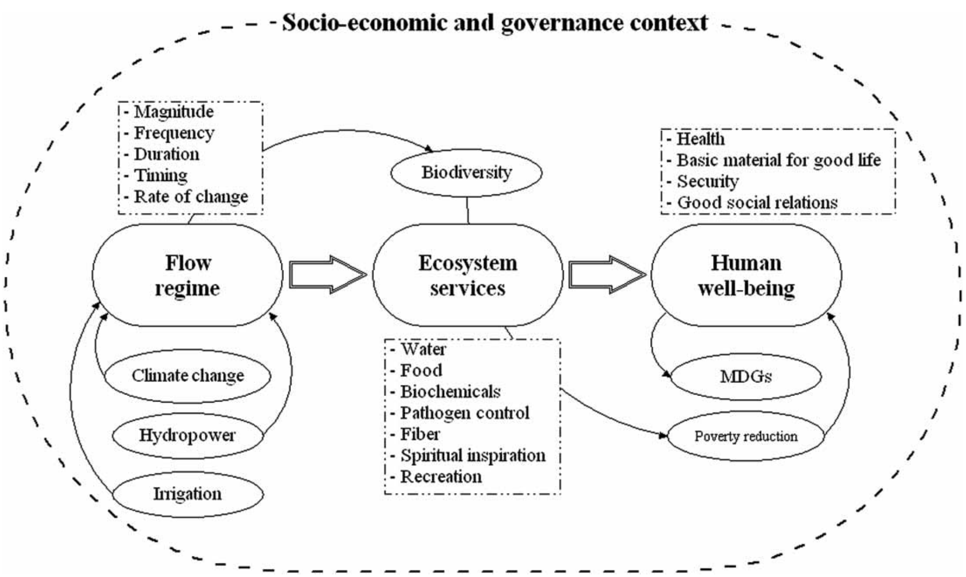

Figure 1 | Linkages between environmental flows and livelihoods (adapted from Richter *et al.* 1996; Millennium Ecosystem Assessment 2005).

low-lying areas will be important in wetter climates or those showing seasonally higher peak flows (Rohde *et al.* 2006). Maintaining environmental flows in association with floodplain restoration, and thereby enhancing natural water storage capacity and decreasing water velocity can manage the likelihood and consequences of flooding events (Welcomme 1979; Junk *et al.* 1989; Clarke *et al.* 2003; Huckstorf *et al.* 2008). In some regions, climate-induced changes in hydrographs may suggest that there are new opportunities to operate dams and power stations to benefit riverine ecosystems (Renöfält *et al.* 2010). Regardless of whether conditions are becoming drier or wetter, we must ensure the rational allocation of water and that resources management decisions are truly negotiated amongst all users (Garrick *et al.* 2009). Negotiating allocation of water for both people and nature within the limits of availability is a challenge made increasingly difficult through climate change.

EMERGING SOLUTIONS

Environmental flows is both a framework and methodology for water resources management decision-making that provides a sound basis for flow management and ES provision under a changing climate. Hydrological analysis and classification of rivers may be coupled with determination of the links between flow alterations and ecological responses (Poff *et al.* 2010) to help preserve drought refugia (Bond *et al.* 2008), spawning water for fisheries during periodic flooding (Huckstorf *et al.* 2008), or enhance ES provision as highlighted in Table 1. Environmental flows information helps identify ecosystem management-based solutions for water resource management challenges including those useful for adapting to climate change. Examples include the protection of forests to recharge aquifers, refilling of wetlands as wetter areas with lower evaporation to increase storage, and reconnecting floodplains to buffer against flood damage. Implementing environmental flow and watershed management re-establishes the natural climate resilience of a river system as it provides a mechanism to 'engineer' environmental outcomes that benefit ecosystems and their users. Although the establishment of environmental water requirements offers a promising means to manage ES (Arthington *et al.* 2010), the role of environmental flows as an adaptation tool becomes more apparent when the hydro-ecological input is incorporated into social processes to balance scientific information with societal values and goals to set environmental flow standards (Poff *et al.* 2010). Policies and governance must also be in place to secure the appropriate management of lands and waters to meet those standards once they are set. More detailed description of environmental flows methodologies and other resources useful for incorporating them into watershed management planning can be found at eFlowNet (2011).

The consideration of climate change in flow studies and water resources planning must involve interdisciplinary cooperation and solutions. Additional drought and flood management planning may mitigate potential water conflicts due to changing water availability with climate change. Consideration of alternative scenarios, analysis of cost and risk, assessment of adaptive capabilities, and interdisciplinary planning are critical components of responding effectively (adaptive management) to the changes ahead (Elmore & Leonard 2009).

The objective of this paper is to show how environmental flow assessments and other biophysical information can be used to better manage watersheds in an ever-uncertain and changing climate, which can be further tempered by socio-economic and development considerations. We also aim to show how eflows assessment as a process can both help create new policies and drive strengthening of existing policies and government institutions essential for implementing watershed management plans once they are developed. Our hypothesis is that setting environmental flow requirements must be based on a process which includes sharing information about watershed function/dynamics and socio-economics under various water allocation scenarios which include changing water availability due to climate change. This is essential but not the only step required to inform decisions on water allocation and ensure sufficient capacity to implement watershed management plans.

We use three case studies to demonstrate the extent to which environmental flow and other biophysical and socio-economic information can help design better management plans for adapting to climate change and increasing resilience, and to what extent this information influences or helps advance policy and institutional reforms necessary for plan implementation – drawing upon both developed and developing world examples.

CASE STUDIES

Three case studies are explored in this section. Tanzania and Southern Africa case studies show the value of environmental flows data and climate change scenario building comparing ecological and economic trade-offs between various land and water use options. This information incorporated into socio-economic contexts is facilitating community-driven decision-making and freshwater ecosystem management as part of better watershed management planning. A third case study in the United States, by contrast, illustrates that data and information are not enough to facilitate better freshwater ecosystem management and watershed planning, instead suggesting a different initial step of institutional and policy reform, given the traditionally rigid nature of institutions and more complex policy realities of climate change. Case study results have implications for environmental flows assessment methods and processes.

The Pangani River Basin (Tanzania)

In Tanzania, like many countries in the world, water has been managed without sufficient attention to river health and other environmental resources that depend on the river. The Pangani River Basin (Figure 2) is one of the four catchment areas administered by the Pangani Basin Water Board, PBWB (previously known as the Pangani Basin Water Office, PBWO). The Pangani River Basin is approximately 43,650 km^2 in size, with about 5% of this area in Kenya, and the remainder in Tanzania. The Pangani River system drains the southern and eastern sides of Africa's highest peak, Mt Kilimanjaro (5,985 m) as well as Mt Meru (4,566 m), then passes through the arid Masai Steppe, draining the Pare and Usambara Mountains before reaching the coastal town of Pangani, marking its estuary with the Indian Ocean.

An integrated environmental flow assessment (IFA) has been undertaken with the PBWB as part of the Pangani River Basin Management Project (PRBMP), to develop an understanding of the hydrology of the river basin, the flow-related nature and functioning of the river ecosystem and the links between the ecosystem and the social and economic values of the river's resources (PBWO/IUCN 2009).

In addition to the IFA, detailed climate change modeling undertaken for the basin has predicted that the seasonality of stream flows in the Pangani is likely to be changed owing to hotter and drier winters (PBWO/IUCN 2010). Based on these climate predictions and using the information from the integrated flows assessment, scenarios

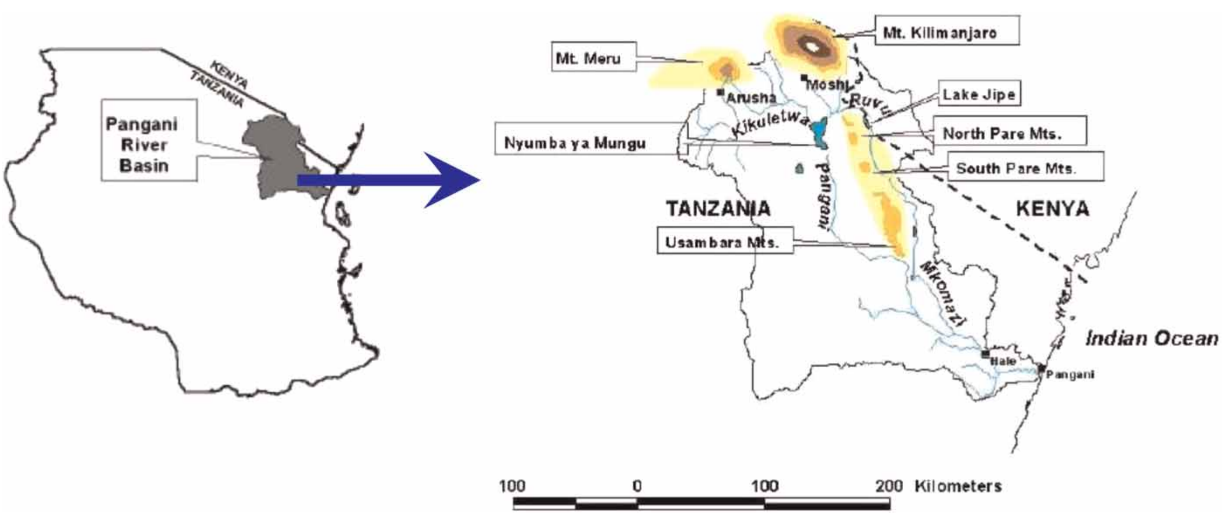

Figure 2 | The Pangani River Basin (*Source:* Pangani River Basin Management Project; Available online at: http://www.iucn.org/about/union/secretariat/offices/esaro/what_we_do/water_and_wetlands/prbmp_esaro/).

looking to 2025 have been developed to determine how different water allocations under this climate future will impact economic development, environmental health, and social well-being in the basin. Hydrological data sets were developed using information from the climate change modeling report, and water resource scenarios were analyzed using this hydrological data (PBWB/IUCN 2011). This information has given further insight into how stakeholders can make social, economic, and environmental trade-offs for different water allocations under possible future climate conditions.

Three of these water development scenarios included maximizing agriculture, where agriculture would be prioritized after meeting the water demands for basic human needs and urban areas. The second scenario is optimizing present day flows with hydroelectric power, describing what could be expected if the present amount of water in the various rivers of the basin was rearranged to provide the best possible flow regimes for river maintenance. Hydropower generation is then given priority use of these flows as they move down the system. A third scenario, optimizing present day flows with storage, describes what could be expected if the present amount of water in the various rivers of the basin was rearranged to provide the best possible flow regimes for river maintenance. Existing infrastructure such as dams was taken into account, but with different operating rules than those in place today. Additional storage was added in the upper basin to allow the capture of some floods and their release in the dry season to ensure the rivers do not dry out (PBWB/IUCN 2011).

Compared with the same scenarios without climate change, the climate change scenarios predicted a reduction in the water available for urban demands, irrigation, and hydropower. They also predicted reductions in flooding of wetland areas, fish catches, and river health. Furthermore, climate change leads to losses in overall economic outputs under all three water development scenarios. Information from the climate scenarios has been used to inform and raise awareness in planning future water allocation. The information derived from the flow assessment, associated climate change studies and scenarios is being used by water governance institutions including the PBWB and sub-catchment level water user associations to make water allocation decisions. The process aims to gradually empower communities and local government to manage conflicts over water resources between upstream and downstream, and between different users such as farmers and pastoralists. Institutional and information gaps between the basin- and national-level processes have been bridged through the IFA study. Likewise, knowledge has been exchanged between the biophysical and socio-economic disciplines as well as between climate change and water sectors.

The Okavango River Basin (Angola, Botswana and Namibia)

The Okavango River Basin is an internal drainage basin which includes parts of Angola, Botswana, and Namibia. The river flows along the border between Angola and Namibia, and then crosses the Caprivi Strip into Botswana where it fans out to form the Okavango Delta (ODMP 2008). The main source of runoff for the basin (95%) is in the highlands of Angola where the Cubango and Cuito rivers start at an altitude of around 1,600 m (ODMP 2008). Annual rainfall averages in the range 1,100–1,200 mm in the Angolan highlands, gradually declining southwards to 480 mm over the delta (ODMP 2008).

The two main contributing rivers in Angola, the Cubango River in the west and the Cuito River to the east, have different hydrological responses to rainfall. The Cubango has a low base flow but this increases rapidly with rainfall. There is a higher base flow in the Cuito which is attenuated in extensive floodplains and swamps. Downstream of where these rivers meet, the main Okavango River tends to produce two major flood peaks reflecting the different contributions of these two tributaries (ODMP 2008).

An IFA was carried out in the Okavango Basin across Botswana, Angola, and Namibia (Figure 3) as part of the Environmental Protection and Sustainable Management of the Okavango River Basin (EPSMO) and Biokavango projects (OKACOM 2010). The goal of the IFA was to provide predictions of ecological, social, and economic change resulting from potential water resource developments in the basin, as a basis for intra- and inter-country discussions on the future basin development pathway (King et al. 2009).

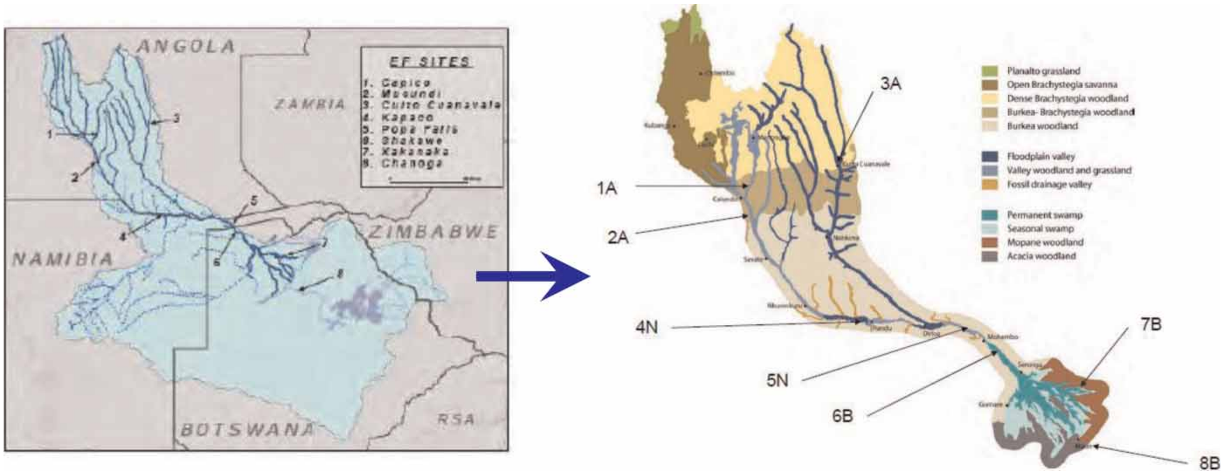

Figure 3 | The Okavango River Basin (*Source:* King & Brown 2009 (left); King *et al.* 2009 (right)).

The assessment used the flow information in a number of scenarios, including low, medium and high water-use development, plus a fourth scenario representing present-day conditions. The low and medium water use development scenarios were overlain with the driest and wettest climate change predictions derived from climate change modeling for the basin (King *et al.* 2009).

In terms of rainfall, there are strong differences between results from various climate change models. In general, an increase in total annual rainfall is projected for the basin, ranging from 5 to 20% compared with the reference period of 1960–1990. Smaller increases are expected in the north part of the basin, and a larger increase in the south. There is expected to be a slight shift in the seasonal distribution of rains. March–May is projected to have the greatest increase in precipitation, while September–November will have the least. Rainfall increase will not be through intensity but rather from a higher number of rain days, so the duration of dry spells is projected to reduce (King *et al.* 2009).

With the described climate change added as an overlay, two possible development pathways were laid out. First, with the drier climate change predictions, there would be reduced localized impacts and increased impacts in the lower catchment (the delta and the outflow). For example, in the delta there would be a moderate shift from permanent swamps to seasonal swamps and savanna under the low development climate change scenario and a more severe shift under the medium development scenario. Second, the wetter climate change predictions would ameliorate the flow-related impacts of development throughout the delta (Helder & Sousa 2009; King & Brown 2009).

As in the Pangani Basin example, the information detailed in the Okavango IFA (ODMP 2008) has been used in basin-wide planning between countries to determine development pathways, and develop adaptation approaches for the different scenarios in order to minimize the impacts of water-related shocks (OKACOM 2010). The Okavango River system is a floodplain-driven system, with floodplains that sustain the river in the dry season and store floodwaters that would otherwise increase flooding downstream. Upstream, the Cuito River has a strong year-round flow and stores floodwaters in its floodplains and then gradually releases water back into the river in the dry season. The riverine ecosystems, along with the ecosystems goods and services used by the population along the lower Okavango River, the Okavango Delta and the outflowing rivers, are sustained mostly by the annual flow regime of the Cuito. To maintain these systems, water resource development along the Cuito, or intervention in the functioning of its floodplains, should be modest and undertaken with extreme caution (King *et al.* 2009).

The Delaware River Basin (USA)

The Delaware River Basin is shown in Figure 4 (DRBC 2011). It lies in the Mid-Atlantic metropolitan corridor and drains portions of four states: New York, New Jersey, Pennsylvania, and Delaware. Even though it is a relatively small watershed (35,066 km^2), it provides water to over 15 million people. New York City draws half of its water supply from the Delaware River headwaters, with a right to transfer up to 35 m^3/s out of the basin. Many downstream industries and municipalities also rely on the waters of the Delaware including the City of Philadelphia. There are 838 municipalities in the basin which together withdraw 32×10^9 m^3/d of water for multiple uses.

All water resource managers have had to manage at the extremes (droughts and floods). The Delaware River Basin Commission (DRBC) has a drought management plan in place that has been effective in all droughts since the 1960s. However, climate change, with sea level rise, changing precipitation patterns, increasing temperature, and vegetation stress (terrestrial and aquatic), will exacerbate these problems. In the Mid-Atlantic area of the USA, sea level rise and atmospheric temperature increase is expected to be larger than the global average estimate. The total annual precipitation is expected to remain stable or increase but with greater storm intensity. More intense storms in winter and spring and drier conditions in the summer are likely to result in increased floods as well as extended periods of drought. There will also be impacts on the land with less snow cover, changing forest type, and probability of more invasive species.

The headwaters of the Delaware River are the most vulnerable to changes in climate and are likely to be impacted by development such as residential and commercial infrastructure and natural gas production. The top third of the Delaware River Basin is underlain by Marcellus and Utica Shales. Water quality may deteriorate as a result of impacts in the sensitive upstream area of the catchment, where forest cover (>85%) is critical to the base flow and water quality of the river. It is likely that the species composition of the forest will change because of increased temperatures and there is a greater potential for invasive species. Erosion and sedimentation will increase as a consequence of higher intensity storms coupled with development pressure that will disturb soils and reduce forest cover. In addition to water being diverted from the headwaters, there is concern in the lower basin due to increasing seawater intrusion from the Delaware Bay if there is not sufficient fresh water flowing down the river. This can cause corrosion at industrial intakes and threaten potable water supplies in Philadelphia and New Jersey. Since the 1950s there has been a US Supreme Court directed agreement among the four states and New York City to manage reservoir releases and river flows aiming to reduce seawater intrusion. The DRBC, an interstate/federal compact commission formed in 1961, is tasked to manage water resources without regard to political boundaries and provides the forum for the five members – the governors of the four basin states and a representative of the President of the United States – to periodically re-evaluate the flow management program and water allocation.

The DRBC promotes integrated water resources management (IWRM) by working at the river basin scale and assessing all potential water supply users and potential impacts. It provides a forum for adaptation as new users or impacts influence flow allocation. For instance, in the 1950s, regulated releases from the New York City reservoirs in the headwaters of the basin were only allocated for human water supply and based on a very specific operating procedure. Currently the flow strategy calls for releases to support ecological flows and a reservoir spill mitigation plan to reduce flood risk downstream, in addition to human use needs. The analysis uses an operating support tool (OST) built by New York City based on an ensemble of factors including season, meteorology, demand, and existing reservoir levels, allowing for greater flexibility.

Planning for additional flows reaching downstream to the bay will be difficult given increased upstream development and water needs for energy production. In addition, the precipitation is projected to occur through greater intensity storms; the existing dams and reservoirs on the major tributaries will not be able to capture as much storm flow as if the precipitation were distributed more evenly over the year. To assess basin-wide water needs, consideration must be given to climate change impacts on salinity repulsion, ecological flow needs, land cover changes, snow pack, evaporation, and storm capture. This analysis needs to be overlain on existing water resource impacts such as population changes and the increase in impervious cover.

Furthermore, overlying the biophysical changes in the Delaware River Basin are challenges that incorporate

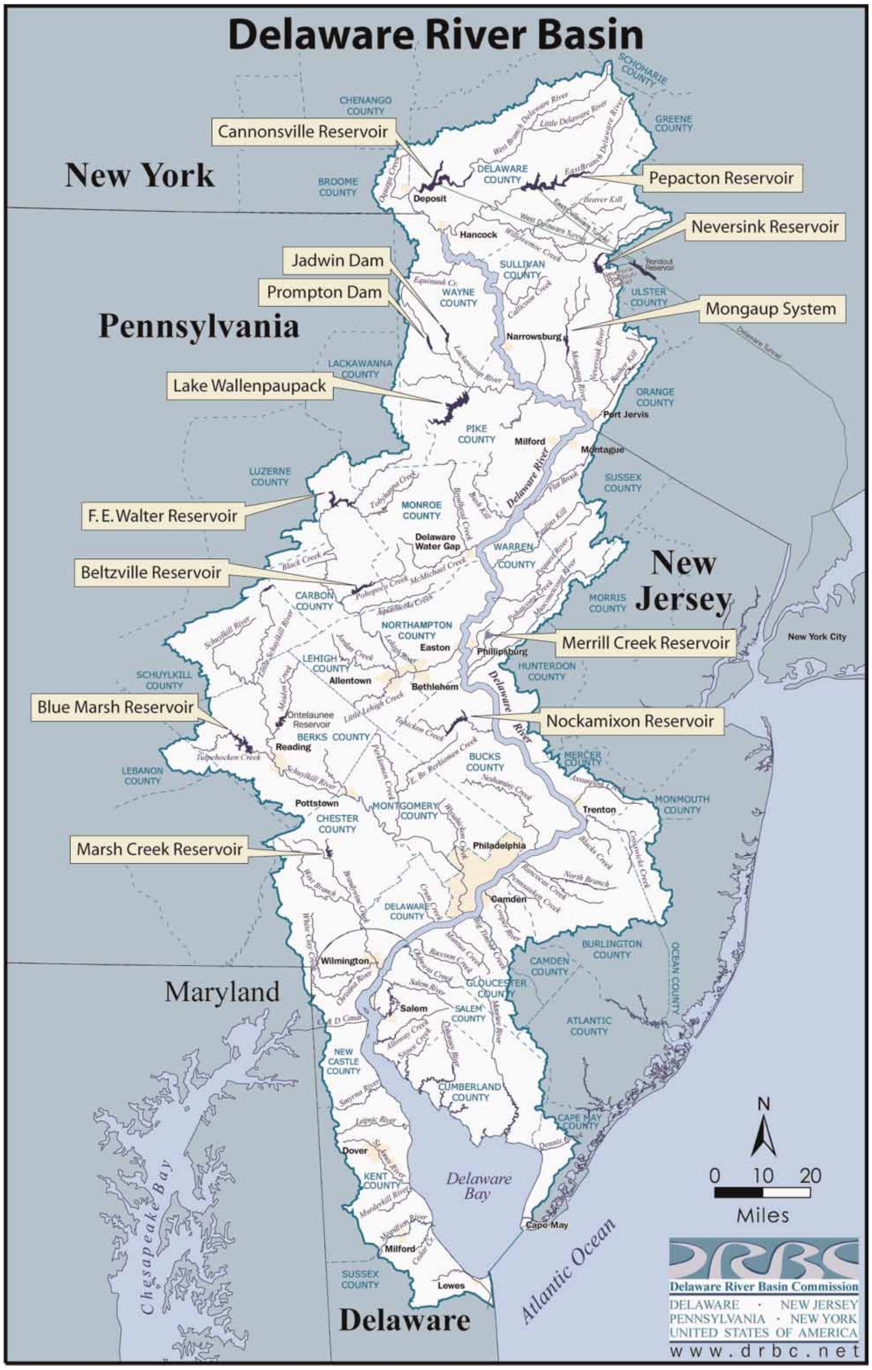

Figure 4 | The Delaware River Basin.

governance complexity, and difficulty in making decisions under uncertainty around water allocation including flows for the environment. There is no one federal water agency, but responsibility for water quality and quantity, biological resources and climatology, which is divided among a number of federal agencies. Land use implementation is the purview of the states sometimes, but more likely the local level of county or municipality. The question is how to allocate flows with the additional pressure of climate change impacts on the system. With unpredictable changes in flows, decision-makers cannot rely solely on historic records. Risk-based analysis is needed to help decision-makers move forward with necessary actions to improve water management and protect critical assets.

As a response, DRBC is developing a basin-wide model to test scenarios of change and potential solutions. The first step is to assess potential flow needs at the head of tide in order to keep the salt line downstream of critical potable water supply intakes. A range of alternatives is used to represent various risk levels (cone of uncertainty). The next step is to look at all the potential influences on water resources in the next 30 years, including a need for increased ecological flows, increased consumptive use by energy generation, and change in population centers and upstream development. Then climate change predictions are overlaid on a series of scenarios based on likely water use changes.

Although integrated planning addresses a range of complexities, climate change can take place on many levels, including wetlands and forests, which could potentially alleviate pollution into the Delaware Bay, increasing urbanization and population pressure. Thus, even excellent regulation and linked management schemes remain inadequate to restore estuary ecosystems to their former conditions. Providing freedom to regional and local bodies to come up with their own solutions and plans to achieving commonly agreed upon goals has empowered a wide variety of groups in the nearby Chesapeake Bay, including local communities and non-governmental organizations, and encouraged them to make a deep commitment, take practical steps, and implement innovative ideas. While an integrated planning approach involving collaboration, coordination, and compromise can be tremendously difficult, it may be the only pathway to a lasting solution (GWP 2011).

Through sensitively testing and working with stakeholders in the basin, a list of opportunities and solutions will be developed. These will be evaluated on the feasibility of short-term and long-term implementation, and human and ecological impacts. Improvements provided by green solutions (e.g. low impact development, water conservation programs, enhanced forested riparian corridors, stormwater regulations requiring more infiltration and post-construction controls, land-use decisions, etc.) will be prioritized before turning towards structural infrastructure improvements (e.g. new reservoirs, flood hazard controls, water system interconnections, etc.). DRBC will be working with a number of state and federal agencies as well as the regulated community, environmental groups, and academic institutions.

DISCUSSION

Climate change complicates the already challenging task of water management, given multiple competing needs and the fact that maximizing some benefits is typically accomplished at the cost of providing other benefits. Multiple stakeholders, water needs, and dynamics of the eco-hydrological system must be considered together. The case studies presented demonstrate that some good tools are being developed to aid in this decision-making, and also suggest what kinds of supporting institutions and policies must be in place to ensure that land and water use decision-making incorporate the needs and benefits provided from freshwater ecosystems.

A few key points emerge from the case studies which can be summarized as lessons learned:

- Holistic water management must be done on a basin or watershed scale. It is the only way to integrate water supply, wastewater, stormwater, and instream flow needs. It is also the way to vertically integrate the different governmental components – national, state, and local – and build stakeholder support through involvement. National and state grant programs should be structured to incentivize IWRM on a basin scale (GWP-TAC 2000). The Pangani and Okavango case studies, and to a lesser extent the Delaware Commission with its next plans, have shown that IWRM frameworks and implementation tools must also include assessment of environmental flows to ensure that benefits are provided to people on a sustainable and long-term basis without degrading the source of those benefits (i.e. freshwater ecosystems).
- The future holds increased uncertainty. Rigid regulatory approaches will not work. There is a need for more flexible management systems built on an initial strategy, implementation, monitoring, assessment, and realignment. Supporting policies and

institutions must be similarly flexible. What makes the experiences with IFAs in the Pangani and Okavango basins also a good example of adaptive management is that science has been used to genuinely make informed decisions rather than to justify already made poor decisions.

- Tools are needed to aid decision-makers in assessing potential futures and implementation alternatives in times of increased uncertainty. These include probabilistic models to use in planning and scenario testing, as in the Delaware experience, and vulnerability assessments which include environmental, social, and economic indicators such as the Pangani and Okavango IFAs. Advanced management tools coupling data-driven modeling (e.g. neural networks, decision trees) with evolutionary optimization (e.g. genetic algorithms, Holland 1975; ant colony, Dorigo 1992) can be considered for creating water management holistic modeling frameworks.
- Climate change models can build upon environmental flow assessments and modeling to see how these changes might impact land and water use decisions. However, engagement of relevant stakeholders is also needed early in the process of building environmental flows and climate change decision-making tools, to result in greater buy-in to decisions made, create new partnerships, and help build stronger water management institutions. New alliances are then created between water managers, policy makers, community members, and scientists, which provide a means of jointly solving watershed management challenges at a sufficiently large scale to avoid unintended trade-offs in water benefits. This has been particularly highlighted by the demonstration of the Pangani IFA but also in the more participatory governance approach proposed for the Delaware Bay.

Other key lessons learned from the case studies include the importance of natural assets for sustaining the livelihoods of rural as well as urban people, many of whom are directly dependent upon these systems and may not be able to afford substitutions once ecosystems are degraded and no longer provide services. Finally, 'no regrets' decisions, where freshwater systems are managed based on best practices that avoid ecosystem degradation, are important means of increasing ecosystem function and resilience, which reduces vulnerability to climate change risk, and can enhance other benefits such as agricultural productivity and hydropower production.

CONCLUSIONS

Addressing climate change impacts within the field of water resources management is complicated. The scale of climatic change and corresponding hydrological changes, particularly when combined with existing pressures, present significant challenges to the sustainable management of the water environment. At the same time, it is critical that we move forward and develop adaptive strategies to cope with climate change consequences.

River systems have a natural capacity to cope with climate variability which has been undermined by canalizing, building dams, diverting water, and so on. Adapting to climate change involves re-establishing the key ES that water systems provide: that of water regulator – providing ways to deal with floods through floodplains and droughts through groundwater-fed base flows. In order to accomplish that, a holistic, integrated approach to water management is required that balances socio-economic, ecological, and technical aspects on different governmental levels. This provides a key role for the scientific community to develop and demonstrate new tools and concepts to aid these environmental flows – like assessments towards a well-informed decision-making process.

This study summarized and extended some of the outcomes of the workshop on 'Climate Change Impacts on Watershed Management: Challenges and Emerging Solutions' held at the IWA World Water Congress and Exhibition, Montréal, 2010, and hosted by the IWA Watershed and River Basin Management Specialist Group. Issues such as governance and decision-making under uncertainty are changing the course of decision-making thinking and implementation to 'no-regrets' risk-based analyses that evaluate standard drivers of change (population movement, impervious cover, etc.) overlain by a number of climate change scenarios (most likely to worst case), all of which need to be integrated in an overall IWRM framework.

REFERENCES

Arthington, A. H., Naiman, R. J. & McClain, M. E. 2010 Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. *Freshwater Biol.* **55**, 1–17.

Bates, B. C., Kundzewicz, Z. W., Wu, S. & Palutikof, J. P. (eds) 2008 *Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change*. IPCC Secretariat, Geneva.

Bond, N. R., Lake, P. S. & Arthington, A. H. 2008 The impacts of drought on freshwater ecosystems: an Australian perspective. *Hydrobiologia* **600**, 3–16.

Bonte, M. & Zwolsman, J. J. G. 2010 Climate change induced salinisation of artificial lakes in the Netherlands and consequences for drinking water production. *Water Res.* **44** (15), 4411–4424.

Brisbane Declaration 2007 The Brisbane Declaration. Environmental flows are essential for freshwater ecosystem health and human well-being. *Declaration of the 10th International River Symposium and International Environmental Flows Conference*. 3–6 September 2007, Brisbane, Australia.

Bunn, S. E. & Arthington, A. H. 2002 Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environ. Manage.* **30** (4), 492–507.

Clarke, S. J., Bruce-Burgess, L. & Wharton, G. 2003 Linking form and function: towards an eco-hydromorphic approach to sustainable river restoration. *Aquat. Conserv.* **13** (5), 439–450.

Daily, G. C. 1997 *Nature's Services: Societal Dependence on Natural Ecosystems*. Island Press, Washington, DC.

Dorigo, M. 1992 *Optimization, Learning and Natural Algorithms*. PhD Thesis, Dipartimento di Electtronica Politecnico di Milano, Milan.

DRBC 2011 Delaware River Basin Commission. Available from: http://www.state.nj.us/drbc/thedrb.htm (accessed 8 February 2012).

eFlowNet 2011 Global Environmental Flows Network. Available from: http://www.eflownet.org (accessed 8 February 2012).

Elmore, L. & Leonard, P. 2009 Incorporating climate change into environmental flows. In: *Proceedings of the 2009 Georgia Water Resources Conference*, April 27–29, 2009, University of Georgia, Athens, GA, USA.

Farrell, T. A., Batker, D., Emerton, L. & Turner, W. 2011 Freshwater ecosystem services. In: *Freshwater: Essence of Life* (C. Goetsch-Mittermeier, R. Mittermeier, T. A. Farrell & I. Harrison, eds). International League of Conservation Photographers, Washington, DC and CEMEX, Mexico City, Mexico, pp. 186–206.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L. & Holling, C. S. 2004 Regime shifts, resilience, and biodiversity in ecosystem management. *Ann. Rev. Ecol. Evol. Syst* **25**, 557–581.

Forslund, A., Renofalt, B. M., Barchiesi, S., Cross, K., Davidson, S., Farrell, T., Korsgaard, L., Krchnak, K., McClain, M., Meijer, K. & Smith, M. 2009 Securing Water for Ecosystems and Human Well-being: The Importance of Environmental Flows. Swedish Water House Report 24, SIWI. Available from: http://www.siwi.org/documents/Resources/Reports/Report24_E-Flows-low-res.pdf (accessed 8 February 2012).

Garrick, D., Wigington, R., Aylward, B. & Hubert, G. (eds) 2009 The nuts & bolts of flow reallocation. In: *Workshop Proceedings, International Conference on Implementing Environmental Water Allocations*, February 22, 2009, Port Elizabeth. The Nature Conservancy, Boulder, CO.

Gleick, P. H. 2009 *The World's Water 2008–2009: Introduction*. Island Press, Washington, DC.

Global Water Partnership Technical Advisory Committee (GWP-TAC) 2000 *Integrated Water Resources Management*, TAC Background Paper No. 4. Global Water Partnership, Stockholm.

GWP (Global Water Partnership) 2011 USA: Chesapeake Bay. Case study #294 for the IWRM Tool Box. Available from: http://www.gwptoolbox.org/index.php?option=com_case&id=184 (accessed 8 February 2012).

Ha Estelle, B. I. Harrison, Barber-James, H., Butchart, S. H. M., Chambers, P., Cordeiro, J., Cumberlidge, N., de Moor, F., Gascon, C., Kalkman, V., van Dijk, P. P. & Yeo, D. 2010 Diversity of species in freshwater systems. In: *Freshwater: Essence of Life* (C. Goetsch-Mittermeier, R. Mittermeier, T. A. Farrell & I. Harrison, eds). International League of Conservation Photographers, Washington, DC and CEMEX, Mexico City, Mexico.

Helder, A. & Sousa, A. 2009 Análise Diagnóstica Transfronteiriça da Bacia do Rio Okavango: Módulo do Caudal Ambiental Relatório do Especialista País: Angola Disciplina: Sedimentologia & Geomorfologia (Okavango River Basin Trounsboundary Diagnostic Analysis. Technical Report). Available from: http://epsmo.iwlearn.org/publications/envana/angola-reports/ (accessed 8 February 2012).

Holland, J. H. 1975 *Adaptation in Natural and Artificial Systems*. The University of Michigan Press, Ann Arbor, MI.

Huckstorf, V., Lewin, W-C. & Wolter, C. 2008 Environmental flow methodologies to protect fisheries resources in human-modified large lowland rivers. *River Res. Appl.* **24** (5), 519–527.

Junk, W. J., Bayley, P. B. & Sparks, R. E. 1989 The flood pulse concept in river floodplain systems. In: *Proceedings of the International Large River Symposium (LARS)* (D. P. Dodge, ed.). Canadian Special Publication of Fisheries and Aquatic Sciences, Ottawa, Canada, pp. 110–127.

King, J. M. & Brown, C. A. 2009 Scenario Report (ecological and social: climate change) Volume 3 of 4. Report 07-2009 EPSMO/BIOKAVANGO Okavango Basin Environmental Flows Assessment Project, OKACOM, Maun, Botswana.

King, J. M., Brown, C. A. & Barnes, J. 2009 Final IFA Project Report. Report 08-2009 EPSMO/BIOKAVANGO Okavango Basin Environmental Flows Assessment Project, OKACOM, Maun, Botswana.

Labat, D., Goddéris, Y., Probst, J. L. & Guyot, J. L. 2004 Evidence for global runoff increase related to climate warming. *Adv. Water Resour.* **27**, 631–642.

Lehner, B., Döll, P., Alcamo, J., Henrichs, T. & Kaspar, F. 2006 Estimating the impact of global change on flood and drought risks in Europe: a continental integrated analysis. *Climatic Change* **75**, 273–299.

Loh, J. (ed.) 2008 *2010 and Beyond. Rising to the Biodiversity Challenge*. WWF, Gland, Switzerland.

Millennium Ecosystem Assessment (MEA) 2005 *Ecosystems and Human Well-Being: Biodiversity Synthesis*. World Resources Institute, Washington, DC.

Neelin, J. D., Chou, C. & Su, H. 2003 Tropical drought regions in global warming and El Niño teleconnections. *Geophys. Res. Lett.* **30**, 2275.

Nijssen, B., O'Donnell, G., Hamlet, A. & Lettenmaier, D. 2001 Hydrologic sensitivity of global rivers to climate change. *Climatic Change* **50**, 143–175.

OKACOM (Permanent Okavango River Basin Water Commission) 2010 Scientific studies aid planning for Okavango River basin. Available from: http://epsmo.iwlearn.org/news-item-folder/scientific-studies-aid-planning-for-okavango-river-basin (accessed 8 February 2012).

Okavango Delta Management Plan Project (ODMP) 2008 *Okavango Delta Management Plan*. Department of Environmental Affairs, Botswana.

Palmer, M. A., Reidy Liermann, C. A., Nilsson, C., Flörke, M., Alcamo, J., Lake, P. S. & Bond, N. 2008 Climate change and the world's river basins: Anticipating management options. *Front. Ecol. Environ.* **6**, 81–89.

PBWO/IUCN 2009 Final Project Report. Pangani Basin Water Board, Moshi and IUCN Eastern & Southern Africa Regional Programme. Available from: http://cmsdata.iucn.org/downloads/final_project_summary_report.pdf (accessed 9 February 2012).

PBWO/IUCN 2010 *Climate Change Modeling for the Pangani Basin to Support the IWRM Planning Process*. Pangani River Basin Flow Assessment, Pangani Basin Water Board, Moshi and IUCN Eastern and Southern Africa Regional Programme, Nairobi, Kenya. Available from: http://cmsdata.iucn.org/downloads/climate_change_modelling_by_uct.pdf (accessed 8 February 2012).

PBWB/IUCN 2011 Pangani River System: Future of the Basin Report. PBWB, Moshi, Tanzania and IUCN Eastern and Southern Africa Regional Programme, Nairobi, Kenya. Available from: http://cmsdata.iucn.org/downloads/future_of_the_basin.pdf (accessed 8 February 2012).

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E. & Stromberg, J. C. 1997 The natural flow regime. *Bioscience* **47**, 769–784.

Poff, N. L., Richter, B. D., Arthington, A. H., Bunn, S. E., Naiman, R. J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B. P., Freeman, M. C., Henriksen, J., Jacobson, R. B., Kennen, J. G., Merritt, D. M., O'Keefe, J. H., Olden, J. D., Rogers, K., Tharme, R. E. & Warner, A. 2010 The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biol.* **55** (1), 147–170.

Renöfält, B. M., Jansson, R. & Nilsson, C. 2010 Effects of hydropower generation and opportunities for environmental flow management in Swedish riverine ecosystems. *Freshwater Biol.* **55**, 49–67.

Richter, B., Baumgartner, J. V., Powell, J. & Braun, B. P. 1996 A method for assessing hydrologic alteration within ecosystems. *Conserv. Biol.* **10**, 1163–1174.

Rohde, S., Hostmann, M., Peter, A. & Ewald, K. C. 2006 Room for rivers: an integrative search strategy for floodplain restoration. *Landsc. Urban Plan.* **78** (1–2), 50–70.

Scholze, M., Knorr, W., Arnell, N. W. & Prentice, I. C. 2006 A climate-change risk analysis for world ecosystems. *Proc. Natl. Acad. Sci.* **103**, 13116–13120.

Schröter, D., Cramer, W., Leemans, R., Prentice, I. C., Araújo, M. B., Arnell, N. W., Bondeau, A., Bugmann, H., Carter, T. R., Gracia, C. A., de la Vega-Leinert, A. C., Erhard, M., Ewert, F., Glendining, M., House, J. I., Kankaanpää, S., Klein, R. J. T., Lavorel, S., Lindner, M., Metzger, M. J., Meyer, J., Mitchell, T. D., Reginster, I., Rounsevell, M., Sabaté, S., Sitch, S., Smith, B., Smith, J., Smith, P., Sykes, M. T., Thonicke, K., Thuiller, W., Tuck, G., Zaehle, S. & Zierl, B. 2005 Ecosystem service supply and vulnerability to global change in Europe. *Science* **310** (5752), 1333–1337.

Van Vliet, M. T. H., Ludwig, F., Zwolsman, J. G. G., Weedon, G. P. & Kabat, P. 2011 Global river temperatures and sensitivity to atmospheric warming and changes in river flow. *Water Resources Res.* **47** W02544, 19.

Verbrugge, L. H. N., Schipper, A. M., Huijbregts, M. A. J., Van der Velde, G. & Leuven, R. S. E. W. 2011 Sensitivity of native and non-native mollusc species to changing river water temperature and salinity. *Biol. Invasions* **14** (6), 1187–1199.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R. & Davies, P. M. 2010 Global threats to human water security and river biodiversity. *Nature* **467**, 555–561.

Welcomme, R. L. 1979 *Fisheries Ecology of Floodplain Rivers*. Longman, London.

World Wildlife Fund (WWF) 2009 *2010 and Beyond: Rising to the Biodiversity Challenge. Living Planet Index*. WWF-International, Gland, Switzerland.

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