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Droughts, floods and freshwater ecosystems: evaluating climate change impacts and developing adaptation strategies

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Abstract. Climate change is expected to have significant impacts on hydrologic regimes and freshwater ecosystems, and yet few basins have adequate numerical models to guide the development of freshwater climate adaptation strategies. Such strategies can build on existing freshwater conservation activities, and incorporate predicted climate change impacts. We illustrate this concept with three case studies. In the Upper Klamath Basin of the western USA, a shift in land management practices would buffer this landscape from a declining snowpack. In the Murray–Darling Basin of south-eastern Australia, identifying the requirements of flood-dependent natural values would better inform the delivery of environmental water in response to reduced runoff and less water. In the Savannah Basin of the south-eastern USA, dam managers are considering technological and engineering upgrades in response to more severe floods and droughts, which would also improve the implementation of recommended environmental flows. Even though the three case studies are in different landscapes, they all contain significant freshwater biodiversity values. These values are threatened by water allocation problems that will be exacerbated by climate change, and yet all provide opportunities for the development of effective climate adaptation strategies.

Additional keywords: climate adaptation strategies, coupled climate–hydrology models, dam reoperation, environmental flows, groundwater, groundwater-dependent ecosystems, land management, surface water.

Introduction

Freshwater ecosystems are among the most imperiled by climate change, largely because of expected changes in their supply and quality of water (Poff *et al.* 2002; Pittock *et al.* 2008). Increased frequency, duration and intensity of drought, changes in the timing and volume of runoff, decreased groundwater recharge, higher rates of evapotranspiration, and increased water temperatures may all result from climate change (Bates *et al.* 2008), stressing species that inhabit or are dependent on freshwater ecosystems (Poff *et al.* 2002). Climate change is only the most recent addition to many existing threats to freshwater ecosystems and their services. The novelty with climate change will be in the rising frequency of extreme events such as storms and droughts, and shifts in the timing of hydrologic events in unregulated river basins (Bates *et al.* 2008).

With many stresses to freshwater ecosystems, climate adaptation strategies are essential to increase or sustain resilience, where resilience is defined as the capacity of the ecosystem to absorb change or shock without collapsing (Holling 1973). Yet to develop these strategies, water managers and conservation planners need to understand potential climate change impacts on streamflows, groundwater levels and aquatic ecosystems. One way to do this is to regionally downscale global circulation models (GCMs), link downscaled climate parameters (e.g. temperature and precipitation) to a hydrologic model, and develop future hydrologic projections (e.g. streamflow, groundwater recharge, watertable elevation) (Xu *et al.* 2005). To understand climate change effects on freshwater ecosystems or components of ecosystems (e.g. species), the modelled hydrologic output can be paired with ecological data or models to determine ecological impacts of changes in hydrology.

Although the number of coupled climate–hydrology models continues to grow, use of these models to guide management decisions remains challenging. Many model outputs are available only at the global scale and are not useful for planning or management at the basin scale (Milly *et al.* 2005). Future hydrologic scenarios and their resulting ecological

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effects are highly uncertain because of compounded errors from the selection of GCMs and future climate scenarios, downscaling, hydrologic models, and determination of ecological impacts from hydrologic changes (Xu *et al.* 2005). Also, many models assume linear relationships between climatic changes and hydrologic responses (Chiew 2006), whereas many freshwater ecosystems experience non-linear, often threshold responses to disturbance (Scheffer *et al.* 2001). Therefore, modelling may be practical in basins with extensive hydrologic and ecological data, but less so in basins where these are limited.

Clearly, adaptation strategies must be developed before sophisticated model outputs for particular basins become available in most regions. These strategies are developed using best available information about the hydrologic regimes in a basin and their likely sensitivity to climate change. Such strategies will need to account for implementation in complex socio-political landscapes with complicated systems of water use and related infrastructure. Thus, freshwater conservation strategies often need to be basin-specific. Given this context, alternative approaches are needed to develop climate adaptation strategies. These must recognise that viable strategies are often underway, including changes in water management and allocation, land-management activities that will buffer freshwater ecosystems from changes in precipitation, and delivery of water allocations to meet ecosystem requirements via engineering solutions. Such ongoing strategies need to be assessed for their relevance against climate change projections, and adjusted as needed, given hydrologic expectations. Such an approach should complement rather than replace the coupled climate–hydrologic modelling work described above. For example, the results of such an exercise can be used to prioritise basins or components of the climate system or hydrologic regime for future modelling work or sensitivity analyses.

The objectives of the present paper were to (1) summarise some of the major impacts of climate change to hydrologic regimes to consider when developing climate adaptation strategies for freshwater ecosystems and (2) present three case studies of climate adaptation strategies developed in the absence of coupled climate–hydrology models specific to those basins. The three case studies highlight ongoing freshwater conservation work in the following three basins: the Klamath Basin in Oregon, USA, the Murray–Darling Basin in Victoria, Australia, and the Savannah River Basin in Georgia, USA. All three basins contain significant freshwater biodiversity and have also many challenges with water allocation among multiple users that will be exacerbated by climate change. Nevertheless, all three basins present different opportunities for balancing water needs among multiple users (including ecosystem allocations) that will potentially make these basins more resilient in the face of climate change.

Climate change impacts to hydrology

Freshwater ecosystems will be directly affected by climate change impacts to water and air temperature, through the form, timing and amount of precipitation, and rates of evapotranspiration (Bates *et al.* 2008). These factors will affect the relationship between precipitation and runoff, as well as groundwater recharge, which will alter flows to and ecology of freshwater ecosystems (Milly *et al.* 2005; Bates *et al.* 2008; Palmer *et al.* 2008). Whereas temperature rise over the next 50 years is predicted with a high level of certainty, the projected changes in precipitation have high levels of uncertainty both within and across models (Bates *et al.* 2008). Changes in evapotranspiration rates also are uncertain, as they depend on a variety of factors, including air temperatures, water availability and the response of vegetation.

Where global data have been downscaled, projected changes in precipitation may vary among models (e.g. Jha *et al.* 2006; Preston and Jones 2008). This uncertainty reduces the models' utility in guiding adaptation strategies for individual watersheds. However, most models suggest a rising frequency of extreme events such as storms, droughts, increases in peak flows and reductions in baseflows, all critical elements to consider in conservation planning for freshwater ecosystems (Bates *et al.* 2008).

In watersheds where streamflow is dominated by low-elevation snow, increasing air temperatures will raise the elevation and decrease the volume of snow accumulation, increase the proportion and frequency of precipitation falling as rain, and shift the hydrograph peak to earlier in the season (Stewart *et al.* 2005; Adam *et al.* 2009). In contrast, snowpack-accumulating watersheds at high elevation will be less affected by rising air temperatures. Watersheds fed by melting glaciers are likely to experience a two-phased response. Initially, streamflow will increase as glacial melt increases, but as the glacier mass declines, streamflow will decline (Schneeberger *et al.* 2003). In watersheds where runoff and streamflow are determined by rainfall rather than snowmelt, global projections indicate variability in changes to flow, but the proportion of wetter basins will decline and the proportion of drier basins will rise over time (Milly *et al.* 2005).

Climate change impacts to ecosystems with significant groundwater flow largely depend on changes in recharge. Climate change will change the timing, distribution and form of precipitation, evapotranspiration, runoff and plant transpiration, which all affect groundwater recharge. Global groundwater modelling shows a decline in groundwater recharge of greater than 10% for more than 20% of the global land area by 2050, with the greatest impacts in arid or semiarid regions (Döll 2009). Groundwater recharge is expected to rise in some areas, which may be problematic where water tables already are high (e.g. Van Roosmalen *et al.* 2007). At a local scale, it is difficult to draw any general conclusions about groundwater flow changes because they are mediated by many factors, including local climate, land cover and geology. In addition, indirect effects resulting from human responses to climate change or changes in land use may be important. For example, a future rise in groundwater pumping is expected, as surface water sources are increasingly depleted and contaminated (Rodell *et al.* 2009), exacerbating the problem.

Response to changes in precipitation, evapotranspiration or temperature can be partly mitigated by management, such as land use and land cover, channel modifications, water storage and water withdrawals. Therein lie opportunities for climate adaptation. The following three case studies from the USA and

Australia outline different approaches to incorporating climate change projections into freshwater conservation strategies.

Case Study 1: land and water management in the Upper Klamath Basin, Oregon, USA

The Upper Klamath Basin spans ~21 000 km^2 on the eastern side of the Cascade Mountains in southern Oregon and northern California. For the present case study, the upper basin is defined as the watershed above Iron Gate Dam, the uppermost of four hydroelectric dams on the Klamath River. Most of the upper basin is semiarid, with predominantly winter precipitation and hot, dry summers. Despite the semiarid climate, the upper basin receives considerable runoff from the Cascade Range and eastern uplands, and also has a substantial regional groundwater flow system (Gannett *et al.* 2007). A variety of aquatic ecosystems occur in the basin, including perennial streams, large shallow lakes, wetlands and numerous groundwater-dependent ecosystems (Brown *et al.* 2010). The area historically supported runs of coho salmon (*Oncorhynchus kisutch*), chinook salmon (*O. tshawytscha*) and steelhead trout (*O. mykiss*), which currently are blocked from the upper basin by the hydroelectric dams on the Klamath River, below the location of this case study. There are no major flow-regulation dams in the upper basin, although numerous diversions provide water for the over 200 000 ha of irrigated agriculture (Gannett *et al.* 2007).

The upper basin faces many challenges in meeting its water resource needs. Because of the semiarid climate, streamflows are naturally low in the summer when agriculture demands are high. Surface water is over-allocated, and once-abundant wetlands have been drastically reduced, resulting in loss of aquatic habitat and natural water storage (Carlson 1993). As a result, there has been conflict over water allocation for the past two decades, involving the federal government, Native American tribes, the farming community and conservationists. Several efforts are underway to meet these water resource challenges. Water rights are currently being adjudicated, including in-stream flows; however, surface waters are likely to continue to be over-allocated and insufficient to meet growing demands. A proposed restoration agreement aimed at resolving water disputes among the parties includes guaranteed water for irrigation, water rights retirement, in-stream flows for fish designated as endangered by the USA *Endangered Species Act*, habitat protection and ecosystem restoration. This agreement is linked to removal of the four hydroelectric dams in the lower basin, downstream of this case study. The agreement could provide an important step in balancing the water needs for people and ecosystems. Although those involved acknowledge the potential impacts of climate change on the water resources of the basin, the proposed strategies have not yet explicitly considered the effects of climate change on water availability. Efforts to do so are limited in part by the lack of coupled downscaled climate–hydrology models specific to this area. Thus, there is a need to determine how the timing and volume of the streamflow will be affected by climate change so that proposed strategies can be refined.

To explore the potential impacts of climate change on the flow in the upper basin, we obtained historic (1979–1991) flow data from stream gauges on three of the principal unregulated stream systems, each with different hydrologic signatures (US Geological Survey 2009). The Sprague River is a combination of surface water runoff, predominantly occurring as spring snowmelt, with a significant groundwater contribution (Fig. 1*a*). The Sycan River is a predominantly surface water-driven

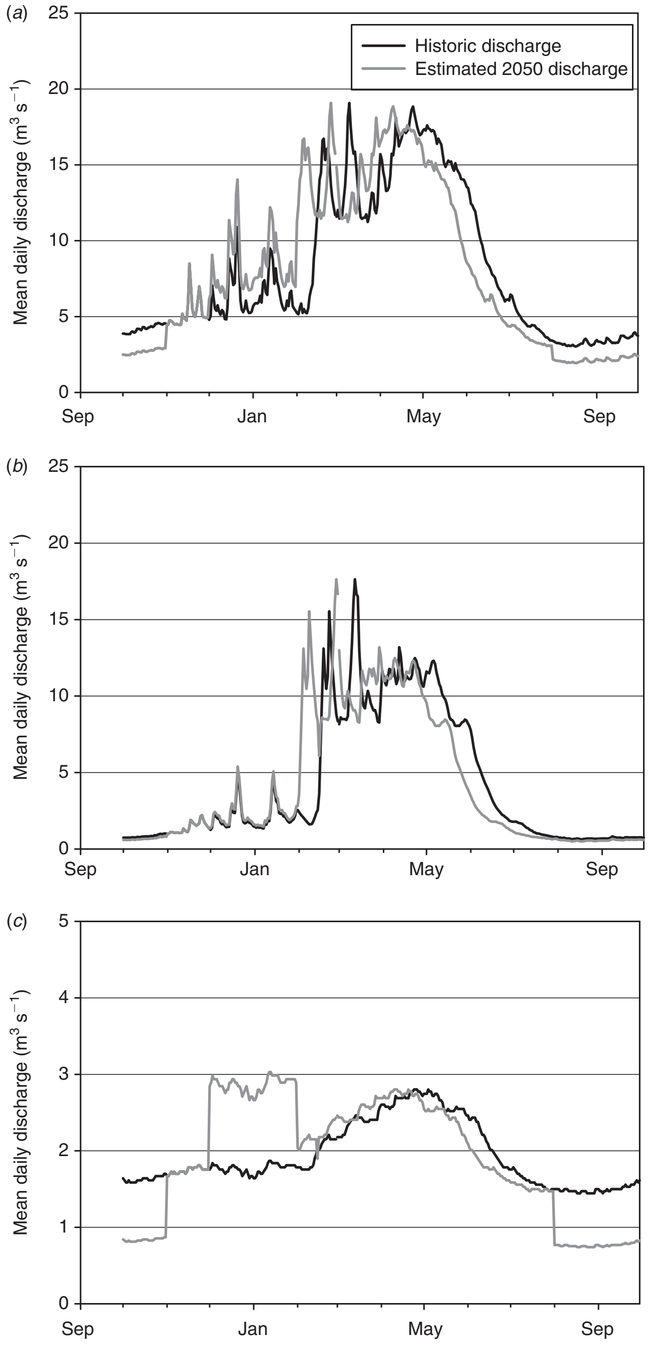

Fig. 1. Hydrographs from Upper Klamath Basin rivers. Black lines show the actual 1979–1991 hydrographs and grey lines show the hypothetical future hydrographs generated in this study, with information described in the text for case study 1, for (*a*) the Sprague River (USGS gauge#11497500 near Beatty), (*b*) the Sycan River (USGS gauge#11499100 upstream of the confluence with the Sprague) and (*c*) the Williamson River (USGS gauge#11491400 near Sheep Creek) (US Geological Survey 2009).

system, with little or no groundwater component, and thus little late-season baseflow (Fig. 1*b*). The upper Williamson River is a predominantly groundwater-driven system with little surface water contribution; ~78% of the mean annual discharge is composed of groundwater in this part of the upper watershed (Fig. 1*c*) (Gannett *et al.* 2007).

We developed quantitative hypotheses for how these hydrographs might be altered by climate change, including hypothetical hydrographs for the year 2050. Streamflow is likely to change with climate change in the Pacific Northwest, including higher flows in the winter, the peak occurring earlier in the spring, and lower flows in the summer (Stewart *et al.* 2005; Adam *et al.* 2009). These predicted changes are driven by increasing temperature and its effects on snowpack, rather than by direct changes to precipitation. The current uncertainty in climate models surrounding precipitation projections is large, with no significant change in precipitation in this region over the next 40 years from current conditions (Adam *et al.* 2009). Thus, when flow data were altered to create hypothetical 2050 hydrographs, we assumed no change in mean annual precipitation, and limited our adjustments to expected changes from increased temperature and its effects on snowpack.

There is an estimated 15–25% decline in late season (August–October) low flow for similar streams in the Cascades in the Pacific Northwest (Tague *et al.* 2008) and a shift in the runoff period of 10–20 days earlier for the Klamath Basin (Stewart *et al.* 2005). Although models predict an increase in winter (December–January) flow, no specific numbers for the amount or percentage of increase were available. In addition to streamflow alteration from changes to melting snowpack, groundwater recharge is expected to occur earlier in the season (Tague *et al.* 2008). Thus, the streams with groundwater contributions (Sprague, Williamson) have additional increased winter flow. We applied all these changes to historic data.

By using the above information, we calculated the new flow amounts in two steps. First, we calculated the reduction to total volume of daily flow over the low-flow period, assuming a 20% flow decline, and subtracted that from the daily means. Second, we increased winter-flow volume by this total amount, distributing it over the specified winter season. We assumed no change in mean annual precipitation (Adam *et al.* 2009), so the total volume of winter-flow increase was equal to the summer decrease. Because the total volume of winter-flow increase was different for each of the three rivers, the percentage increase also varied, being 10% in the Sycan, 17% in the Sprague and 26% in the Williamson. Although we had no quantitative data for changes in groundwater, the calculated winter-flow increases matched relative groundwater contributions. So, the Sycan River, with no groundwater contribution, had the lowest percentage winter-flow increase, whereas the Williamson, with the greatest groundwater contribution, had the greatest percentage winter-flow increase. In addition to changes in flow magnitudes, we shifted the timing of streamflow 2 weeks earlier for winter snowmelt, and spring to early summer flows.

These changes were applied to the three existing hydrographs to generate hypothetical hydrographs resulting from climate change (Fig. 1). Whereas shifts are often reported for monthly or seasonal time periods (e.g. Tague *et al.* 2008), we applied these shifts to daily time-series data to retain the spikes in the hydrograph that are lost with reporting of monthly means. Thus, the 2050 hypothetical hydrographs are not always continuous at the transitions between months. When comparing the historic and hypothetical 2050 hydrographs, streamflow in different hydrologic regimes will fare differently in a changing climate. The largest relative declines in baseflow are in the Sprague and Williamson, whereas baseflow declines are not as apparent in the Sycan. Large seasonal shifts are seen in the Sprague and Sycan, because of their dependence on snowmelt-driven runoff.

Depending on the hydrologic regime, the impacts to water resources will vary; thus, strategies to address these shifts should vary by sub-basin and hydrologic regimes. One of the strategies included in the proposed restoration agreement is a voluntary reduction of irrigation water diversions; however, current efforts to identify farms for this voluntary program do not account for climate change and assume no change in irrigation season streamflows. As the hypothetical shifts in the hydrograph demonstrate, the amount of reductions needed could be even more challenging for farmers, as late-season flow diminishes, particularly in the Sprague and Williamson sub-basins. Additional strategies of protecting and enhancing the natural capacity of the watershed for capturing, storing and releasing water may be necessary to buffer this decline in flow. This includes restoration and reconnection of floodplain wetlands along the Sprague and Sycan Rivers, which depend heavily on surface-water runoff. Because agricultural lands are identified for reducing water demands, an additional consideration in the selection process should be given to areas that can increase the natural storage of water during the winter season. Side channels, floodplains, and intact riparian areas also provide important aquatic habitat and stream shading that maintain cool stream temperatures critical for salmonids and other native aquatic species in these watersheds.

Another important strategy is to protect groundwater recharge zones, because recharge may decrease in the future (Döll 2009). This is especially critical in the Sprague and Williamson watersheds, where groundwater is a significant component of the hydrograph. For these watersheds, more work is necessary to determine the most important groundwater recharge zones, and to identify land-use practices that protect and enhance groundwater recharge. Ensuring viable and sustainable groundwater resources will benefit both people and groundwater-dependent ecosystems.

Streamflow in the Sycan River is dominated by surface water (Fig. 1). Whereas the Sycan and similar streams already go nearly dry in the summer, the shifts in the hydrograph as a result of climate change could significantly shorten the season of available irrigation water, and cause additional stress to aquatic ecosystems. Because the predominant source of water is snowmelt, it is essential that climate change adaptation strategies consider watershed management and restoration that captures and retains winter snow. Timber harvesting and associated land management, including the size, location and configuration of harvest units, affect snow capture and subsequent melting (National Research Council 2008), and so these impacts should be considered in future harvest management plans. This will be particularly important for low-elevation snow zones, where the snowpack is most vulnerable to climate change (Nolin and Daly 2006).

Although no coupled climate–hydrology models are available currently for the Upper Klamath Basin, it is possible to use the existing information to consider how climate change may affect different streams with different relative contributions of surface water and groundwater. By dissecting the hydrograph, we can identify key climate change adaptation strategies that address some of these impacts. This approach is a powerful tool for rethinking the highest priorities for freshwater protection, restoration and conservation, as well as to prioritise future climate- and hydrology-modelling work.

Case Study 2: flood requirements for the floodplain forests and wetlands in the southern Murray–Darling Basin

The 1 061 469-km^2 Murray–Darling Basin in south-eastern Australia covers one-seventh of the continent and parts of four states and one territory. The basin is considered the ‘foodbowl of Australia’, producing 40% of the country’s agricultural products (including cropping, grazing and horticultural activities). Australia’s three longest rivers, the Darling, Murray and Murrumbidgee are found here.

The Victorian floodplain forests and wetlands in the south of the basin are some of the most threatened and, until recently, under-reserved ecosystems in Australia (Robertson and Fitzsimons 2005; Fitzsimons 2006). Pulsed flooding is the major factor influencing biota in river-floodplain systems (Ballinger and Mac Nally 2006). The river red gum forests of northern Victoria and southern New South Wales provide an important refuge and corridor for many species adapted to floods and wet environments in a semiarid landscape. The forests and their associated wetlands contain significant cultural and environmental values and are internationally recognised for their importance to a wide range of endemic and threatened species, including migratory birds (VEAC 2006).

Reduced flooding to wetlands and floodplain forests, resulting from dams, diversions, over-allocation of water for agriculture and differences in governance for river management among the different jurisdictions have altered the ecology of many freshwater ecosystems (Kingsford 2000; Pittock *et al.* 2008). Some floodplain wetlands also have been converted to permanent storage to supply water for agriculture, changing biota (Kingsford 2000). As a result, many river reaches in the Murray–Darling are in poor condition (Davies *et al.* 2008).

In addition to the recent prolonged drought, climate change is expected to further stress aquatic ecosystems in the Murray–Darling Basin. Many wetlands and floodplain forests are receiving far less water than in the past (VEAC 2006; Pittock *et al.* 2008). The lower Murray–Darling Basin has a precipitation-dominated hydrograph and climate change predictions for the region are for increased mean annual temperatures and reduced total annual precipitation (Jones and Durack 2005). Current climate change predictions have been fed into a hydrological sensitivity model where percentage change in the mean annual rainfall and potential evaporation are used to estimate the percentage change in the mean annual streamflow (Jones and Durack 2005; Preston and Jones 2008). Generally, a decrease in rainfall of 1% results in a 2–3% decrease in runoff to rivers (Chiew 2006). As the catchment dries out, rainfall is required simply to saturate the soils.

The challenges currently posed by water over-allocation and problems with water delivery will only increase with future climate change. Therefore, a critical climate change adaptation strategy for this basin is an improved approach to identifying ecological values and priorities and increased flexibility in delivery of water to ecosystems. To assist in the decision-making for environmental water allocation for protected areas and other public land, a process for identifying flood-dependent natural values on the Victorian floodplains of the River Murray and its tributaries was developed (VEAC 2008*a*). The Victorian Environmental Assessment Council (VEAC) sought out and compiled data on flood requirements (e.g. natural flood frequency, critical interval between floods, minimum duration of floods) for all flood-dependent ecological vegetation classes and rare and threatened species along the Goulburn, Ovens, King and Murray Rivers in Victoria (VEAC 2008*b*). Past environmental water allocations in Victoria have targeted ‘icon sites’ and various natural assets (e.g. stressed river red gum trees (*Eucalyptus camaldulensis*), colonial nesting waterbirds, various fish species) (Leslie and Ward 2002; Stewart and Harper 2002), with limited consideration of the water requirements of the full suite of floodplain ecosystems and significant species. By considering the flood requirements of the full range of natural assets, the effectiveness and efficiency of water delivery for biodiversity outcomes can potentially be significantly improved.

The approach recommended by VEAC in its final report (and subsequently accepted by the Victorian Government), differed from draft recommendations for environmental water only a year earlier, where a specified amount (4000 GL every 5 years) has been recommended to achieve environmental flows, particularly in the form of overbank flows (VEAC 2007). The change in approach partly resulted from new estimates of future runoff which took climate change into account and suggested that the average amount of water available for environmental flows is estimated to be reduced by as much as 32% under moderate climate change scenarios, or 44% if the past 10 years of drought continued (Jones and Durack 2005; DSE 2008; VEAC 2008*b*). The climate change scenarios of reduced precipitation, increased temperatures and resultant reduced runoff also imply that natural overbank flows may not occur in many parts of the system. Therefore, many wetlands will be reliant on targeted environmental allocations. Artificial delivery of this water may be the most efficient or only option. For example, slight alterations of the heights of existing weirs can allow water to spill into the floodplains of the north-western forests of Wallpolla, Lindsay and Mulcra Islands (MDBC 2006).

New infrastructure, either permanent or temporary, is now essential for delivery or maintenance of environmental flows for many parts of the basin. For example, temporary pumps transferred water from the Murray River into the Ramsar-listed Hattah Lakes in 2006 and 2009, with similar arrangements pumping smaller amounts into floodplain forests downstream. Flow regulators on creeks in most of the major floodplain forests along the Murray River are used to manage flows, and particularly to retain water in these forests. Although these regulators have improved the ability to distribute and better target priority places with less water, their operation poses problems for particular species (such as fish stranded as water recedes from the floodplain) (Jones and Stuart 2008). Furthermore, although the 'engineered solutions' outlined above might be suitable for emergency management of some values (e.g. river red gums), they do not replace the function of natural overbank flows on which many species rely as part of their lifecycle (VEAC 2008*b*). There are different problems for wetlands in the Victorian Riverina bioregion, isolated from the floodplain and reliant on either flooding of tributaries of the Murray River or local rainfall. Many natural or semi-natural wetlands were 'dumps' for unwanted irrigation water about a decade ago (e.g. Kingsford 2000). However, the decade-long drought and trading of water among districts on the open market (e.g. from the irrigated pasture of the Kerang district to the vineyards and fruit trees of Mildura) have reversed this, leaving many of these wetlands without significant water in the past decade. Dryland farming is taking over irrigation areas in these regions and irrigation channels are falling into disrepair, limiting their future capacity to deliver environmental water to these wetlands. Ensuring that some irrigation channels remain functional will be important for efficient delivery of environmental water to isolated wetlands.

This case study demonstrates that an ongoing freshwater conservation strategy can be adapted to future climate change projections, where current stresses to water quantity and environmental flow regimes are similar to those from climate change. Overall, the approach outlined above is intended as the start of an adaptive process allowing for the incorporation of monitoring and feedback over time. For example, as more information becomes available on floodplain ecological vegetation classes and species and climate change model projections, water allocations can be more targeted. The key issue will be transparency and communication of the extent to which manipulated or natural flows benefit various natural values. Quantitative and visual outputs such as maps of flood-dependent vegetation types and threatened species habitat will enable environmental managers and the public to easily identify which values benefit from and which values miss out on water (see VEAC 2008*a*).

Case Study 3: environmental flow management of the Savannah River, Georgia and South Carolina, USA

Beginning in the Blue Ridge Mountains of northern Georgia, USA, the Savannah River traverses more than 500 km in its path to the Atlantic Ocean. A rich variety of aquatic systems occur in the 27 000-km^2 basin, including aquatic shoals, bottomland hardwood forests, tidal wetlands, longleaf pine (*Pinus palustris*) forests, Carolina bays, granite outcrops and bluff forests. The waters of the Savannah River provide habitat for ~100 species of fish – one of the most diverse fish assemblages in the south-eastern United States (Richter *et al.* 2006). Many of these fish species are widely known to anglers, such as largemouth bass (*Micropterus salmoides*) and striped bass (*Morone saxatilis*). Several rare fishes are also found in the Savannah River, including the robust redhorse (*Moxostoma robustum*) and two species of sturgeon (*Acipenser* spp.). Freshwater mussels are also abundant in the river system, including nine rare species (Richter *et al.* 2006).

The US Army Corps of Engineers (hereafter, 'Corps') operates three large dams on the river – Hartwell, Russell and

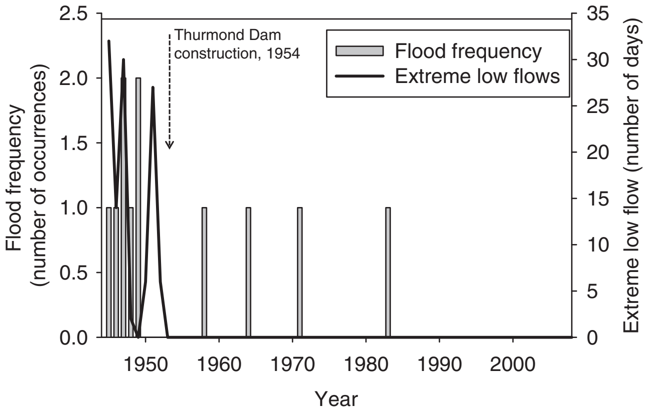

Fig. 2. Flood frequency (grey bars, number of occurrences per year) and extreme low flow (lower than 10th percentile of baseflows) in the Savannah River (black line, number of days with extreme low flow per year).

Thurmond Dams – all upstream of Augusta, Georgia. Constructed between 1954 and 1984, these are multi-purpose dams for hydropower generation, flood control, recreation, water supply and fish and wildlife habitat. Operation of the Corps dams is a dominant control on the hydrologic regime in the lower Savannah River. Typical of many regulated river systems (Poff *et al.* 2007), the dams have dampened extremes in river flow by substantially lowering flood flows and augmenting downstream low flows by releasing water from reservoir storage during dry periods (Fig. 2). Elimination of the highest and lowest flows has had a substantial impact on riverine, floodplain and estuarine biota, and resulted in consequences for commercial and recreational fisheries and timber production in the floodplain.

As a result of growing concerns about the deteriorating health of the river ecosystem, the Corps contacted The Nature Conservancy to identify ways to modify dam operations to benefit the river. The Conservancy designed a year-long scientific assessment to develop environmental flow recommendations for the Savannah River (Richter *et al.* 2006). An environmental flow workshop brought together scientists and technical experts from a variety of disciplines, including fish and aquatic biologists, floodplain forest ecologists, estuarine ecologists, fluvial geomorphologists, hydraulic engineers and hydrologists. The resulting environmental flow recommendations for the Savannah River specify the flow levels to be attained, for varying lengths of time, during each month of the year, along with the hypothesised ecological responses. The following three aspects are of particular importance for aquatic species: (1) multiple high flow-pulse events each spring, (2) higher (i.e. flood) flows every 2–3 years in the spring and (3) very low flow during the summer.

During the spring season (January–April), multiple 'high flow pulse' events are critically important. They support ecological functions such as fish migration to upstream spawning habitats, access to food-rich floodplain habitats for fish and dispersal of tree seeds throughout the floodplain. Less frequently (average 2–3 years), higher (flood) flows are needed to physically rearrange the channel and floodplain. These floods provide physically diverse habitats for aquatic organisms and sustain ecologically important floodplain habitats such as wetlands and oxbow lakes. However, such floods have occurred much less frequently in the Savannah River since Thurmond Dam was constructed in 1954 (Fig. 2). Extreme lows also have not occurred since dam construction (Fig. 2). These allow the river to drop to very low levels during the summer (May–September) and are essential for floodplain trees, such as bald cypress (*Taxodium distichum*), to regenerate.

Efforts to implement the environmental flow recommendations began in March 2004 and focussed only on releasing moderately high flow pulses during spring. Urban development immediately downstream of Thurmond Dam constrains the Corps' ability to safely release large flood events, and downstream industrial wastewater discharges into the river requires adequate flow in the river to dilute these discharges, thus preventing the Corps from reducing river flows to very low (natural) levels.

Some of the hydrologic changes anticipated with climate change are forcing the Corps to consider novel water management strategies for the Savannah River. Similar to the regions of the United States where the river hydrograph is dominated by rainfall, the Savannah River basin is expected to experience increasingly severe and frequent droughts, increased winter and decreased summer rain, and a change in the seasonality of peak events (Neff *et al.* 2000; Bates *et al.* 2008). These trends will greatly challenge the Corps to sustain current levels of water supply, hydropower generation, wastewater dilution and flood protection at its Savannah River dams. For example, rainfall events of a 20-year recurrence or greater could cause extensive damage to homes and other urban buildings constructed since the dam. The degree to which rainfall intensity will increase remains difficult to predict, although extreme rainfall events are likely to become more frequent. Additionally, the water supply and hydropower generation of the Corps' dams will be strained with increasing severity of droughts. Although the flood control, water supply and hydropower functions of these dams are already vulnerable to hydrologic extremes, these functions are expected to be placed under much greater risk with climate change. In the face of this potential crisis, there are opportunities to improve dam operations.

Two strategies under consideration for the Savannah River could greatly increase the Corps' flexibility to manage the hydrologic system under climate change, while also substantially improving implementation of environmental flow recommendations. One of the two strategies is to improve the wastewater quality from industries along the lower Savannah River, reducing the necessity for dilution flows. The Corps could then drop water levels, achieving a key aspect of the environmental flow recommendations. The second strategy involves building a structural floodway through the city of Augusta, Georgia, to enable the Corps to safely release flood events from its dams. Presently, the Corps cannot release flows greater than $850\,m^3\,s^{-1}$ from the dam without flooding some areas of the city. However, a new floodway with a capacity of $550\,m^3\,s^{-1}$ or greater could enable dam releases at the level deemed necessary to restructure channel and floodplain habitats ($1400\,m^3\,s^{-1}$). Importantly, this would also increase flexibility to manage flood risk as the climate changes.

This Savannah River case study illustrates that many water management systems are already tenuous and vulnerable, regularly failing to meet different expectations. In these stressed management contexts, environmental flow releases from dams are commonly the first benefit to be dropped during dry times. Climate change may be the 'final straw' on the Savannah, forcing managers and stakeholders to pursue novel strategies. The remedy to lessen risks of flood protection, reductions of water and energy should align with increasing opportunities to provide environmental flow releases.

Discussion and conclusions

The three basins discussed are in different parts of the world, with different climates and different types of water uses. Yet they share much in common with each other, and with many basins worldwide. All three contain important and significant freshwater biodiversity that is both imperiled and worthy of protection. Conservation activities are ongoing in all three basins, with environmental water allocations recognised as critical for multiple ecosystem values. In all three cases, climate change is one more addition to the long list of stressors, including river regulation, over-allocation of available water, or drought.

Although there is little that can be done to halt climatic changes over the next 50 years at the river basin level, much is possible to address how those changes are manifest in river basins worldwide. In the Upper Klamath Basin, water and land management actions and priorities can buffer changes to streamflow because of changes in the form, timing and distribution of precipitation. In the Murray–Darling Basin, water delivery systems may need to be engineered differently to deliver environmental water allocations to important ecosystem attributes. In the Savannah River Basin, technologies to improve wastewater management and engineering for better flood routeing could allow dam managers to meet recommended environmental flows.

The uncertainty associated with climate change impacts, coupled with the multiple unknowns associated with implementing large-scale changes in water and land management, necessitate a robust monitoring program that is specifically linked to adaptive management scenarios. This can refine implementation as climate change model scenarios become more precise, track the effectiveness of strategy implementation, and change ineffective strategies. Furthermore, monitoring should attempt to measure ecosystem resilience, i.e. how close the system is to a tipping point beyond which it will collapse (e.g. Folke *et al.* 2004; Brook *et al.* 2008).

Such changes in river basin management could have been made in the past, and were not. However, there is hope in these and many other places that the value of strategies designed to increase the resilience of freshwater ecosystems will be recognised because of the high-profile nature of the threat of climate change, or else because of the increasing recognition that many human and natural water systems lie close to thresholds of major degradation associated with climate change. Indeed, with climate change as an added stress to ecosystems, which are already threatened by multiple pressures, ignoring potential solutions for increasing ecosystem resilience is foolhardy.

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