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Climate Change and River Ecosystems: Protection and Adaptation Options

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Abstract Rivers provide a special suite of goods and services valued highly by the public that are inextricably linked to their flow dynamics and the interaction of flow with the landscape. Yet most rivers are within watersheds that are stressed to some extent by human activities including development, dams, or extractive uses. Climate change will add to and magnify risks that are already present through its potential to alter rainfall, temperature, runoff patterns, and to disrupt biological communities and sever ecological linkages. We provide an overview of the predicted impacts based on published studies to date, discuss both reactive and proactive management responses, and outline six categories of management actions that will contribute substantially to the protection of valuable river assets. To be effective, management must be place-based focusing on local watershed scales that are most relevant to management scales. The first priority should be enhancing environmental monitoring of changes and river responses coupled with the development of local scenario-building exercises that take land use and water use into account. Protection of a greater number of rivers and riparian corridors is essential, as is conjunctive groundwater/surface water management. This will require collaborations among multiple partners in the respective river basins and wise land use planning to minimize additional development in watersheds with valued rivers. Ensuring environmental flows by purchasing or leasing water rights and/or altering reservoir release patterns will be needed for many rivers. Implementing restoration projects proactively can be used to protect existing resources so that expensive reactive restoration to repair damage associated with a changing climate is minimized. Special attention should be given to diversifying and replicating habitats of special importance and to monitoring populations at high risk or of special value so that management interventions can occur if the risks to habitats or species increase significantly over time.

Keywords River · Climate change · Management options · Land use change · Floods · Droughts

Introduction

In the late summer of 1958, the greatest anadromous fish disaster in history was unfolding on the Snake River near the small town of Oxbow, Idaho in the United States. Chinook salmon and steelhead had started their fall

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spawning run but became stranded in stagnant, un-aerated pools of water just below the 205-foot Oxbow Dam. By the end of the season, 10000 fish had perished before spawning (Barker 1999). This dam became the focus of a major fight pitting power needs against concerns over the environmental health of a river. There is even greater concern today about the future of rivers worldwide due to a multitude of stressors that impact running waters including climate change. We draw on the growing literature related to climate change to illustrate potential impacts rivers may experience and management options for protecting riverine ecosystems and the goods and services they provide. Regional patterns in precipitation and temperature are predicted to change and these changes have the potential to alter natural flow regimes. The ecological consequences and the required management responses for any given river will depend not only on the direct impacts of increased temperature but on how extensively the magnitude, frequency, timing, and duration of runoff events change relative to the historical and recent flow regime for that river, and how adaptable the aquatic and riparian species are to different degrees of alteration.

It will become clear that climate change is not the only risk most rivers face because most rivers are within watersheds affected by human activities including agriculture, urbanization, or suburban development or, like the Snake River (Fig. 1), they are affected by dams. Thus, management options for climate change often overlap with and include actions that influence human use of the land or water. Given the potentially large impact of human land use and climate changes, the ability of a river to provide desired ecosystem goods and services (Table 1) in the future will depend increasingly on how it is managed. Without deliberate management actions that anticipate future stress (proactive management), managers will be left "reacting" to problems (reactive management) that come along, and the provision of ecosystem services from rivers will not be guaranteed (Palmer and others 2008). We illustrate our points primarily using U.S. river examples but the main points are applicable worldwide.

Fig. 1 Photo of Snake River below Hell's Canyon Dam. Photograph courtesy of Marshall McComb, Fox Creek Land Trust

River Futures and Multiple Sources of Stress

Anticipating the future condition of a river in the face of climate change requires explicit consideration of two things: where the river sits on the globe with respect to its climate, hydrology and ecology; and, how human activities affect the river and its ecosystems (Table 2). Even if human impacts are small at present, unless the river is within a fully protected basin, impacts associated with human activities are likely to become issues in the future and thus, climate change and other potential stressors must be considered simultaneously (Kleinen and Pedschel-Held 2007). In many areas, the ecological impacts from human activities will far exceed the impacts from climate change (Scholze and others 2006) but there is also evidence that factors such as urbanization will interact with climate change in ways that may determine the impacts to aquatic biota (Nelson and others 2009). While these drivers are important, recent studies on a number of rivers have confirmed measurable impacts of climate change that are independent of other drivers (Dai and others 2009; Durance and Ormerod 2009).

One of the key ways in which climate change or other stressors affect river ecosystems is by causing changes in river flow. Rivers vary geographically with respect to their natural flow regime and this variation is critical to the ecological integrity and health of streams and rivers and thus a great deal has been written on the topic (Poff and others 1997; Postel and Richter 2003). For every region of the world there is a range of natural flow regimes representative of the unaltered landscape and reflective of the interaction of precipitation, temperature, soils, geology, and land cover. Some regions have very stable, constant flows due to sustained groundwater inputs and rainfall patterns while others are extremely flashy with discharge increasing dramatically and this increase may be predictable or unpredictable (Poff and others 1997). These different flow regimes support very different ecological communities. For example, Montana's Upper Missouri River supports extensive stands of native cottonwood trees along the riverbanks. These trees become established during annual peak flows that overtop the banks and create favorable establishment conditions during the annual snowmelt runoff event. In contrast, Florida's Wekiva River is a flat-water system heavily influenced by groundwater and streamside wetlands that store and release water to the

Table 1 Rivers and streams provide a number of ecosystem services that are critical to their health and provide benefits to society; major services are outlined along with examples of the hydrological, geomorphic, and ecological processes that support each service and some of the consequences if services are lost

Ecosystem services	Supporting processes and structures	Consequences of losing the service
Water purification		
(a) Nutrient processing	Retention, storage or removal of excess nitrogen and phosphorus; Decomposition of organic matter.	Excess nutrients can build up in the water making it unsuitable for drinking or supporting life; Algal blooms can lead to anoxic conditions and death of biota.
(b) Processing of contaminants and pollutants	Plant and microbial uptake or transformation that limits downstream flux of contaminants and pollutants. Reduction of suspended sediment and sediment transport by plants and geomorphic features.	Toxic contaminants, suspended sediments and other pollutants can kill or impair biota; Water not potable.
Water supply	Transport and storage of water throughout watersheds.	Loss of water for residential, commercial and urban use; Loss of irrigation supply for agriculture.
Flood control	Intact floodplains, wetlands and riparian vegetation buffer large increases in discharge by physically slowing water flow, temporarily storing water or removing water through plant uptake.	Without the benefits of floodplains and riparian wetlands and vegetation, increased flood frequency and flood magnitude are common.
Water storage	Intact floodplains and riparian wetlands; Vegetation increases infiltration of rain water and increases aquifer recharge	Droughts exacerbated; Loss of groundwater stores for private and public use; Loss of vegetation and wildlife.
C and N sequestration		
(a) Primary production	Aquatic and riparian plants and algae store C and N temporarily by converting CO_2 and N into biomass.	Atmospheric levels of NOx and CO_2 build up contributing to global warming.
(b) Secondary production	Consumers ingest and store carbon	
Food Production		
(a) Primary production	Production of new plant tissue	Reduction in food and food products derived from aquatic plants such as algae, rice, watercress, etc.
(b) Secondary production	Production of new animal tissue or microbial biomass	Decreased secondary production can lead to shortages in fisheries including finfish, crustaceans, shellfish, etc.
Biodiversity	Diverse freshwater habitats, watersheds in native vegetation, dispersal and exchange of genetic material, natural disturbance regimes, primary productivity and complex trophic interactions.	Loss of aesthetic and recreational features, impacts aquarium trade, potential destabilization of food web or depressed ecosystem function.
Temperature regulation	High heat capacity of water; Changes in water temperature buffered by riparian soil infiltration and shading by riparian vegetation.	If infiltration or shading are reduced (due to clearing of vegetation along stream), stream water heats up beyond what biota are capable of tolerating
Erosion/sediment control	Soil held in place or trapped by intact riparian vegetation; Geomorphic features and algae reduce erosive forces on streambank and streambed.	Aquatic habitat burial impacts fisheries and biodiversity, causes increase in contaminant transport, reduces downstream reservoir storage or impacts coastal regions
Recreation, cultural, inspirational value	Clean water, particularly water bodies with pleasant natural surroundings such as forests and natural wildlife refuges are natural wonders	Lost opportunities for people to relax, spend time with family; Economic losses to various industries, particularly tourist oriented ones

C = carbon, N = nitrogen

river over the year thus creating a highly stable flow regime that supports a great diversity of plant species and community types.

Anthropogenic Impacts on Rivers

The impact of human activities on streams and rivers has been reviewed extensively elsewhere and so we provide only a brief overview. Most rivers have some level of alteration in their surrounding landscape. Because rivers are integrators of changes in a watershed, they are also often indicators of ecological degradation beyond their banks. The primary impacts on rivers will continue to come from water withdrawals, dams, and land cover change.

The depletion of river flows by excessive withdrawals fundamentally alters aquatic ecosystems because it reduces the quantity of habitat available, and alters the temperature and chemistry particularly during low-flow periods (Poff and others 1997). During the latter half of the 20th century,

Table 2 The potential impacts of climate change on river ecosystems may be exacerbated by anthropogenic stressors; examples are provided to illustrate categories of change and common complicating stressors; however, a very large number of combinations are expected around the world and some complicating stressors may be present in all regions (e.g., invasive species)

Effects of climate change	Examples of impacts	Common complicating stressors	U.S. example
Early snowmelt	Species life histories temporally out of synch with flow regime	Dams, flow diversions or changes in reservoir releases	Pacific Northwest
More flooding	Flood mortality, channel erosion, poor water quality	Development in watershed	Northeast, Upper Midwest
Droughts, intense heat	Drought mortality, shrinking habitat, fragmentation	Over-extraction of water; Invasive Species	Southwest
Little change in rainfall, moderately warmer	Impacts modest unless complicating stressors	Development in watershed; Over-extraction of water	Northern Florida, Mississippi, parts of middle and western states

water withdrawals in the United States more than doubled but appear to have leveled off in some regions (Hutson and others 2004).

As withdrawals were increasing, the building of dams and storage of water in reservoirs helped to meet water and energy needs and we are now seeing a similar expansion of dam building in developing countries such as China. While dams provide substantial benefits to local or regional economies (World Commission on Dams 2000) they come at great cost to a river's ecological health (Postel and Richter 2003; Schelle and others 2004). Dams create barriers for upstream-downstream movements of mobile aquatic species such as anadromous or catadromous fish (Silk and Ciruna 2005). Dams also have considerable influence on river ecosystems such as fundamentally altering the natural flow regime, changing water temperature (Todd and others 2005) and chemistry (Ahearn and others 2005), sediment transport (Vörösmarty and others 2003) and floodplain vegetation communities (Tockner and Stanford 2002).

Conversion of natural land cover to human uses has also had a substantial influence on rivers, particularly by reducing the natural abilities of landscapes and adjacent riverine ecosystems to absorb and filter water flows. Farming has introduced major pollutants in freshwater ecosystems including excessive sediment, fertilizers, pesticides (Silk and Ciruna 2005) and urbanization has further degraded rivers and streams (Walsh and others 2005). As the amount of cleared land and impervious surface area in a watershed increase, there is an increase in runoff, higher peak discharges, higher sediment loads, and reduced invertebrate and fish biodiversity (Dunne and Leopold 1978; Arnold and Gibbons 1986; McMahon and Cuffney 2000).

Climate Change Impacts on Rivers

During the 21st century, the average global temperature is projected to increase by 1.8–4.0°C (IPCC 2007a). Increases in surface air temperature associated with climate change will vary seasonally and will be greater in some regions than others thus more strongly affecting rivers (Rosenzweig and others 2008). Because streams and rivers are generally well mixed and turbulent, they respond to changes in atmospheric conditions fairly easily and thus they will become warmer (Eaton and Scheller 1996; Kaushal and others 2009). At higher latitudes temperature changes will be pronounced as will changes in discharge due to earlier snowmelt (Milner and others 2009). Significant warming trends (1–3°) have already been documented in streams and rivers for which long term temperature records are available (Durance and Ormerod 2007, 2009; Barnett and others 2008, Kaushal and others 2009). Rivers fed by groundwater should be somewhat buffered from atmospheric heating at least in the short term.

Projections for precipitation are more uncertain than for temperature. Current projections (Hayhoe and others 2007; Seager and others 2007) suggest that in the U.S. there could be up to a 15% increase in winter precipitation in the Northeast and as much as a 10% decrease or more in the Southwest. Little or only small changes in total annual precipitation are expected in many other regions; however, the distribution of that rain throughout the year will likely vary. For example, recent evaluations of climate models for Maryland suggest that the magnitude and frequency of spring floods and summer droughts may increase (Boesch 2008). An increase in the number of days with severe thunderstorms (but not necessarily more total rainfall annually) may extend well beyond Maryland to much of the Atlantic coast and the Gulf of Mexico (Trapp and others 2007).

In regions that receive most of their precipitation as snow, the increased temperatures may result in a shift from winter snow to rain or rain plus snow (Barnett and others 2008). A recent analysis of long-term United States Geological Survey (U.S.G.S.) discharge records showed that most rivers north of 44° North latitude—roughly from southern Minnesota and Michigan through northern New York and southern Maine—have had progressively earlier winter-spring streamflows over the last 50–90 years (Hodgkins and Dudley 2006). Rivers in mountainous regions are likely to experience earlier snowmelt, and in most regions, less snowpack (McCabe and Clark 2005; Stewart and others 2005).

Over the last 50 years, the amount of runoff has changed substantially for many rivers (Fig. 2) due to the combined effects of withdrawals, dams, and climate (Milliman and others 2008). For a subset of these rivers, human influences on annual flows are small compared with climatic forcing (Dai and others 2009). For example, river flows in southeastern Australia (e.g., the Murray Darling River), in central and western Africa (e.g., the Congo and Sahel Rivers) and in the northwestern U.S. (e.g., the Columbia River) have declined while rivers draining to the Gulf of Mexico (the Mississippi) and to the Arctic region have increased flows (Dai and others 2009). Because of the projected changes in CO_2 and the resulting changes in temperature and precipitation, river discharges are expected to continue to change in many regions potentially much faster than they have historically (Lettenmaier and others 1994; Vörösmarty and others 2000; Alcamo and others 2003). Projecting the exact magnitude and direction of change for an individual river is not easy; predictions can vary significantly depending on which modeling approach is used and what assumptions are made (Kleinen and Pedschel-Held 2007). For example, while most predictions of future Colorado River flows are for decreases (some quite substantial; Seager and others 2007) there have been some recent projections of increased flows (National Research Council 2007).

To help cope with some of the uncertainty in forecasts, Milly and others (2005) evaluated global fields of relative (i.e., percent) change in runoff using 12 different models. For the United States, their median projections are for increased annual runoff over the Midwest and Middle-Atlantic, slightly decreased runoff in the Missouri River Basin and the Texas Gulf drainage, substantial decreases in annual runoff in the Southwest (Fig. 3), and substantial increases in runoff for Alaska. In regions in which snowmelt occurs earlier due to warmer temperatures, stream flows will increase early in the season and flooding may be pronounced if high flows coincide with heavy rainfall events. A shift in the timing of springtime snowmelt toward earlier in the year is already being observed (1948–2000) in many western rivers (Fig. 4), particularly in the Pacific Northwest, Sierra Nevada, Rockies, and parts of Alaska (Stewart and others 2004). However, recent work by Tague and others (2008) suggests that local differences in groundwater inputs to streams may mediate hydrological changes due to a changing climate (Tague and others 2008).

Interaction of Climate Change and Anthropogenic Stressors

The effects of multiple environmental stressors on ecosystems are still poorly understood but those most likely to intensify the negative effects of climate change include land use change and excessive extractions of river water or groundwater that feed rivers (Kundewicz and others 2008; Nelson and others 2009). Rivers in watersheds with a significant amount of urban development are expected to experience the greatest future changes in average temperature as well as temperature spikes immediately following rain storms (Nelson and Palmer 2007; Nelson and others 2009) (Fig. 5). The number of extreme flow events would also increase under future climates particularly in urbanized basins (Kleinen and Pedschel-Held 2007). Thus, flooding may become a more serious problem in regions of the United States with more rainfall and more urbanization

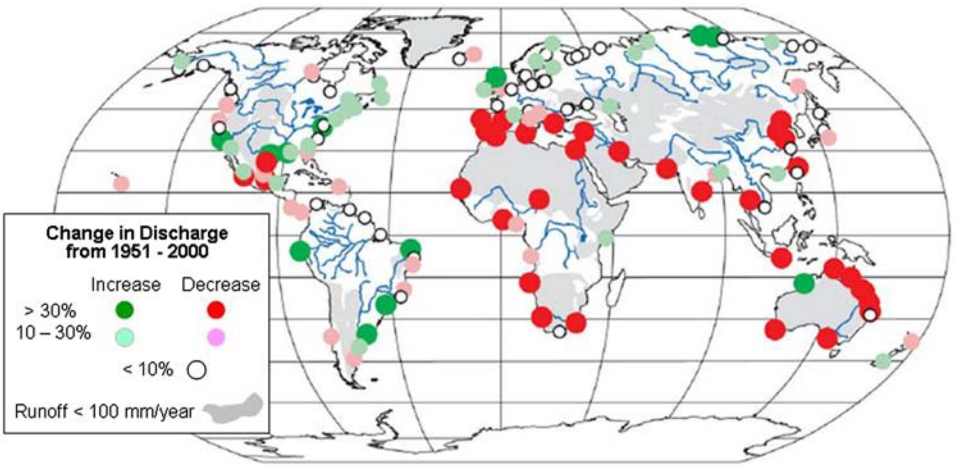
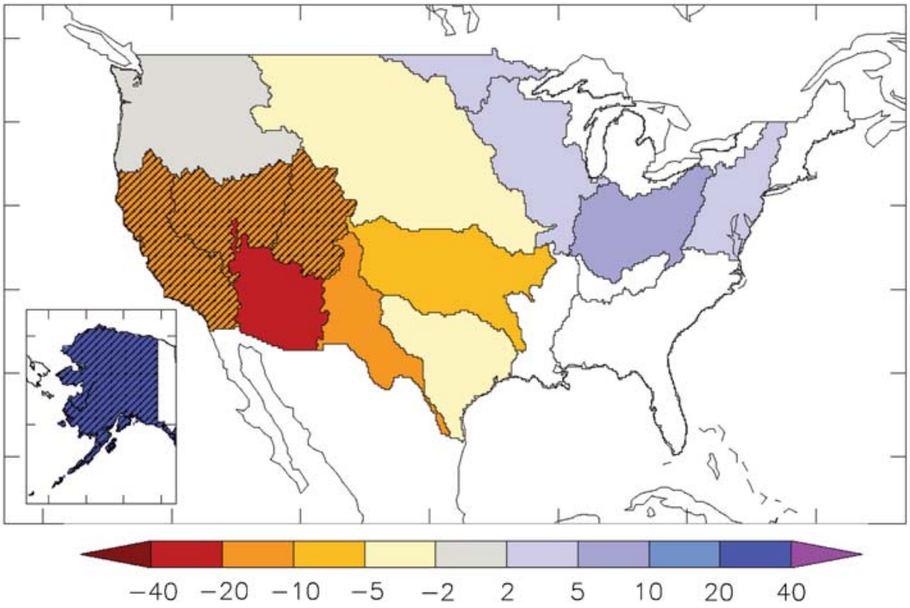


Fig. 2 Historical (1951–2000) discharge trends for 137 global rivers (cumulative annual discharge to the oceans). With the exception of the Kolyma, Lena, and Fraser Rivers, <10% changes are not statistically significant. Increases were largely due to more precipitation; most rivers with large decreases influenced by dams, irrigation, and inter-basin transfers. Gray shaded regions represent water-scarce areas, mean annual runoff <100 mm/yr. Modified from Milliman and others (2008)

Fig. 3 Median, over 12 climate models, of the percent changes in runoff (colored scale) from United States water resources regions for 2041–2060 relative to 1901–1970. More than 66% of models agree on the sign of change in areas shown in color (white = little or no change); diagonal hatching indicates greater than 90% agreement. From Milly and others (2005) after re-plotting with data provided courtesy of P.C.D. Milly. (Color figure online)



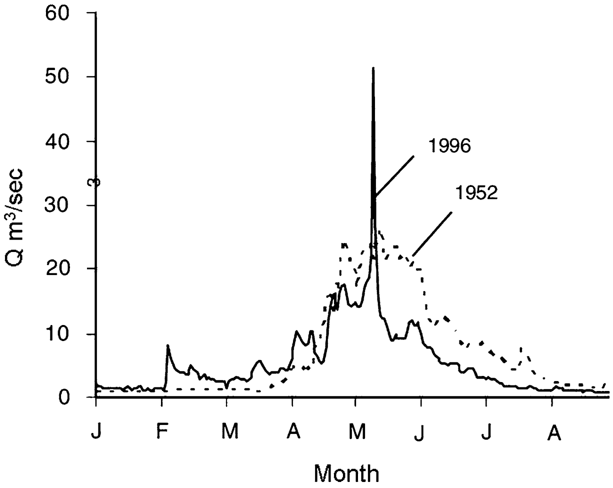


Fig. 4 Earlier onset of spring snowmelt as show by changes in daily average discharge in 1996 versus 1952 in the Carson River, California, U.S. In 1996, discharge 'spikes' occurred starting in February instead of later in the spring. Such trends are occurring in many snowmelt-fed river basins in the western U.S. Modified from Stewart and others (2005)

in the future (e.g., the Northeast and portions of the mid-Atlantic) (Nowak and Walton 2005; Boesch 2008).

Excessive water extractions are already affecting some U.S. rivers (e.g., the Rio Grande) and this impact will be exacerbated in regions expected to experience even more water stress due to climate change coupled with population growth (e.g., southeastern U.S. and south Asia). Alcamo and others (2007) used a global water balance model to simulate the combined impacts of climate change and future water stress due to socioeconomic driving forces (income, electricity production, water-use efficiency) that influence water extractions. Their models indicate that for the 2050s, areas under severe water stress will include not only parts of Africa, Asia, and the Middle East, but also the western United States. This may mean that in dammed rivers, drawdown of reservoirs will occur, with less water available to sustain environmental flows in the downstream rivers. In regions expected to experience increased precipitation or early snowmelt on top of rain, flooding problems may increase, particularly if climate change brings greater intensity of rainfall. For dammed rivers, managers may need to adjust dam operating plans to avoid catastrophic high releases of water into downstream areas.

The Ecological Prognosis

The impacts of climate change on river ecosystems will depend on the rate and magnitude of change relative to historical and recent thermal and flow regimes for each watershed. Changes outside the natural range of flow or temperature variability may have drastic consequences for ecosystem structure and functions depending on the rate of change in temperature or discharge relative to the adaptive capacity of species (Poff and others 2002). River ecosystems in regions that experience changes that are modest relative to historical and recent regimes will have fewer negative impacts particularly if watersheds are relatively free of human impacts (Palmer and others 2008). For a given change in temperature, free-flowing rivers in protected watersheds are expected to be the most resistant and resilient to climate change because temperature and flow changes are buffered compared to clear-cut or urbanized watersheds (Nelson and others 2009). Glacially influenced

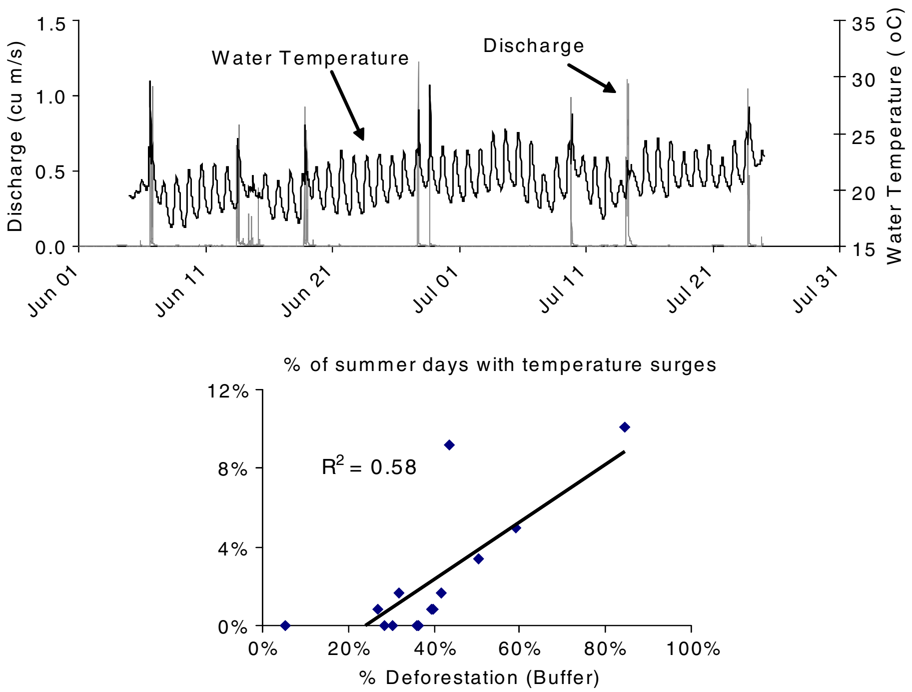


Fig. 5 Very rapid increases (1–4 h) in water temperature (temperature "spikes") in urban streams north of Washington D.C. have been found to follow local rain storms. *Top graph:* dark line shows stream discharge that spikes just after a 2002 rainfall in watersheds with large amounts of impervious cover; gray line shows temperature surges that increase 2–7°C above pre-rain levels and above streams in undeveloped watersheds in the region. In highly urbanized regions, there is no temperature buffering effect that is typical in wildlands where rain soaks into soil, moves into groundwater, and laterally into streams. Instead, in these urbanized sites water moves quickly over land and hot pavement directly into streams. *Bottom graph:* shows that the number of temperature surges in a stream during the summer months increases as the amount of stream buffer in forest declines ($n = 16$ sites; $P = 0.001$; $r^2 = 0.58$). Modified from Nelson and Palmer (2007)

river basins are very sensitive to climatic shifts and some projections suggest warming temperatures may lead to an increase in species richness of plants and invertebrates even if some cold stenothermic taxa are lost (Milner and others 2009).

Species-Level Impacts

Individual growth and reproductive rates of fish are expected to increase as the water warms unless thermal tolerances of any life history stage are exceeded; typically, eggs and young juveniles are the most sensitive to temperature extremes (Van der Kraak and Pankhurst 1997; Beitinger and others 2000). Faster growth rates and time to maturation typically result in smaller adult size and, because size is closely related to reproductive output in many aquatic invertebrates (Vannote and Sweeney 1980), population sizes may decline over time. The thermal tolerance abilities of aquatic insects influence acclimation capacity such that species with high upper thermal limits will fare best under a warming climate (Calosi and others 2008). If upper thermal tolerance for many aquatic insect species is associated with a limited geographic range as Calosi and colleagues (2008) showed for 13 species of diving beetles, then insect species at risk are likely those with the most restricted present distributions.

River biota with good dispersal abilities may be able to shift their distributions. However, habitat loss and/or the absence of northern flowing rivers may restrict movement of fish and prevent those that require prolonged periods of low temperatures from moving to colder regions (Mathews and Zimmerman 1990). Similarly, riverine insects with adult flying stages that require vegetated corridors for dispersal may not survive if vegetation loss or changes in composition occur (Allan and Flecker 1993). For fish, amphibians, and water-dispersed plants, habitat fragmentation due to dams or the isolation of tributaries due to drought conditions may result in local extirpations (Dynesius and others 2004) such as those found in the southwestern U.S. by Fagan and others (2002). Similarly, fish that depend on high-elevation snowmelt streams for spawning may be seriously impacted if discharge in these remote streams is changed significantly due to earlier snowmelt (Battin and others 2007) and they can not shift their spawning times or adjust to the new flows (Ficke and others 2008).

Xenopoulos and Lodge (2006) showed that there is a statistical relationship between large river discharge and fish diversity globally and used this to build scenarios of change in fish diversity due to climate change and other anthropogenic drivers that reduce river discharge. Applying this approach at global scales they predicted that in rivers with reduced discharge, biodiversity of fish may be dramatically impacted (up to 75% threatened) by 2070 due to the combined effects of climate and water extractions (Xenopolus and others 2005). However, such projected rates of species loss need to be adjusted for regional differences in natural flow regimes, as seasonally intermittent rivers may be more vulnerable than perennial ones (Poff and others 2001). Even if streams do not become intermittent, those that experience reductions in baseflow (e.g., in the southwestern U.S.) may have stressed biota and riparian vegetation (Allan 2004). As flow levels drop and temperature increases, dissolved oxygen levels will decline and critical habitat for current-dependent (rheophilic) species may be lost (Poff 2002).

For rivers in which discharge exceeds historical and recent bounds, species may be lost unless they are capable of moving to less-affected regions. Assuming adequate sediment supply, with higher flows come higher suspended sediment and bedload transport, which may interfere with feeding and reproduction. If sediment deposition fills interstitial spaces, this will reduce hyporheic habitat availability for insects and spawning areas for lithophilic fish (Pizzuto and others 2007; Nelson and others 2009). Whether deposition or net export of these sediments occurs will depend on the size of the sediment moving into channels in concert with peak flows (i.e., the stream competency). Particle size and hydraulic forces are major determinants of stream biodiversity (both the numbers and composition of algae, invertebrates, and fish) and excessive bottom erosion is well known to decrease abundances and lead to dominance by a few taxa (Allan and Castillo 2007).

Impacts on Ecological Processes and Water Quality

Many of the ecological processes supporting the provision of clean water will be influenced by higher water temperatures and altered flows and primary production in streams is well known to be very sensitive to these two factors (Lowe and Pan 1996). Of course CO_2 will also be higher in the future unless drastic measures are taken to reduce emissions. We have not yet discussed the potential for elevated levels of CO_2 to impact river ecosystems because impacts are largely indirect (e.g., on temperature); however, it is worth briefly visiting the topic in the context of algal and riparian plant growth. Recent experiments showed that primary production of benthic stream algae doubled in response to elevated CO_2 levels and resulted in higher amounts of low quality algal food for invertebrate consumers compared to ambient CO_2 treatments (Hargrave and others 2009). In these experiments, the density, biomass, and average size of individual consumers responded positively to the higher biomass of algae suggesting that total algal food and not quality may be more important for these invertebrates.

The response of riparian plants to elevated CO_2 has also been studied. Growth rates increase for the riparian trees that have been studied, their leaves have more carbon-rich compounds like phenols and lignins, and the chemical changes persist in leaf litter (Rier and others 2005). Dissolved organic carbon (DOC) leaching from the chemically altered litter is more refractory (Kominoski and others 2007). Despite these changes, the growth rates of stream fungi and bacteria on this litter or when grown with DOC leachate from the litter, did not change relative to rates in ambient CO_2 treatments; however, stream algae grown with the more refractory DOC had lower levels of chlorophyll a and was less preferred by crayfish consumers than algae from ambient CO_2 treatments (Kominoski and others 2007).

These studies illustrate the complicated ways in which ecological processes (primary productivity, decomposition, microbial production, and consumer growth and feeding preferences) can be affected by changes in CO_2 levels. The picture may be even more complex once potential interactive effects between changes in temperatures, flow regime, CO_2 and other stressors are explored. For example, while riparian plant growth may respond positively to higher CO_2 when it is the only environmental factor altered, riparian plants growing in regions that are warmer and drier are expected to have reduced growth rates and waters receiving their litter inputs are expected to have reduced particulate (POC) and dissolved organic carbon concentrations (Williamson and Zagarese 2003). With lower POC and DOC levels, UV-B penetration will go deeper in the water and could reduce productivity of freshwater algae and negatively impact benthic invertebrates (Hader and others 2007).

With respect to water quality, there is general agreement it will be negatively impacted in regions that experience large temperature increases (Kundzewicz and others 2008). If intense storms lead to increased turbidity and pollutant loads, water quality problems will be further exacerbated (Nelson and others 2009). Analysis of a 26 year data set for 50 southern British streams showed that reduced water quality (lower oxygen, phosphate and ammonia) was more likely the cause of changes in stream invertebrate communities than were direct thermal or discharge impacts on the fauna (Durance and Ormerod 2009). In France's Rhone River, however, higher temperatures combined with lower oxygen levels best explained changes in stream invertebrate communities (Daufresne and others 2004). Changes in river water quality associated with changes in nitrate export from watersheds have also been explored given climate change projections. Wright and others (2007) suggest that total nitrate flux to rivers may not change but may be distributed differently throughout the year due to shifts in the timing of precipitation. Others have shown long term trends (both positive and negative) in nitrate concentration in streams and it appears that patterns result from complex interactions between increased temperature, changes in the magnitude and timing of discharge, amount of nitrogen deposition, and amount of snowpack (de Wlt and others 2007). In short, with respect to issues of ecological processes, the direction and magnitude of impacts (or lack thereof) from climate change will be context specific.

Adaptation Options

Rivers are inherently dynamic systems—in their native state they are constantly adjusting to changes in sediment and water inputs by laterally migrating across the landscape and by changing the depth, width, and sinuosity of their channels. These changes are part of a healthy river's response to changes in the landscape and the climate regime. However, as emphasized earlier, the new temperature and precipitation regimes expected as a result of climate change will occur much more quickly than historical climate shifts (IPCC 2007b) and because many rivers are affected by development, dams, and water extractions, their ability to adjust to changes in the flux of water and material may be impaired (Palmer and others 2008). Thus, the amount of ecological change will depend on the rate of temperature change which will vary regionally, the extent to which a watershed is already impacted by human activities, or both. For example, the entire watershed of the Noatak River (Alaska) is fully protected but because of its high latitude it is already experiencing very large temperature shifts which are expected to have serious consequences for migrating salmon and other highly valued species (National Research Council 2004). In contrast, temperature change will be relatively less in the Delaware River Basin (borders Pennsylvania, New York, Delaware, New Jersey) but water extractions, reservoirs, and other human activities in the watershed mean ecological impacts could be significant and plans to protect drinking water sources are required (Rosenzweig and others 2007).

Following Palmer and others (2008), we distinguish between *proactive* and *reactive* management actions for adapting to climate change. The former includes management actions such as restoration, land purchases, and measures that can be taken now to maintain or increase the resilience of rivers. Reactive measures involve responding to problems as they arise by repairing damage or mitigating ongoing impacts. Some actions are far more desirable to undertake proactively (e.g., acquire land to protect floodplains), others may be done proactively *or* reactively (e.g., riparian restoration), and some should only be undertaken if damage to a river is severe (e.g., reconfiguring a channel).

Reactive Management

Without adequate preparation now, managers may be forced to respond to events such as floods, droughts, erosion, and species loss as they occur. Extreme flow events may lead to substantial erosion of river banks that not only place sensitive riparian ecosystems at risk but may cause water quality problems downstream due to higher suspended sediment loads (Nelson and others 2009). At the other extreme, arid regions that experience more droughts may find populations of valued species isolated due to dropping water levels (Ficke and others 2008). Reactive management efforts may be needed to stem future degradation of ecosystems or extirpation of a species.

The most expensive and serious reactive measures will be needed for rivers in basins that are heavily developed or whose water is managed for multiple uses. In rivers with significant increases in discharge, river restoration projects to stabilize eroding banks or projects to repair in-stream habitat may be needed. To prevent future occurrences, more stormwater infrastructure should be put in place. Other measures such as creating off-channel storage basins or wetland creation may be a way to absorb high flow energy and also maintain water quality (Poff 2002). Removing sediment from the bottom of reservoirs could be a short-term solution to allow for more water storage, perhaps averting dam breaches that could be disastrous; however, if rates of sediment accumulation in reservoirs increase under future climates, this may become logistically difficult. Water quality problems due to high sediment loads or contaminants may impact river reaches downstream of developed (urbanized or agricultural) regions, and these problems are very difficult to cope with in a reactive manner (Nelson and others 2009).

In regions with higher temperatures and less precipitation, reactive projects might include fish passage projects to allow stranded populations to move between isolated river reaches during drought times, replanting of native riparian vegetation with drought resistant vegetation, or removal of undesirable non-native species that take hold. If dams are present, flow releases during the summer could be used to sustain flora and fauna in downstream river reaches that are drying up. These are simply examples of reactive management that are discussed more fully in Palmer and others (2008) but the most important point is that a reactive approach is not the most desirable response strategy to climate change, because a high degree of ecosystem and infrastructure damage is likely to occur before reactive measures are taken and this may even risk human life (Kirshen and others 2008). Delayed responses could result in the flooding of homes and highways in populated regions. If reactive management is the only option then continuous evaluation of river health over time with rigorous monitoring is imperative so that management changes begin as soon as problems are detected, i.e., before problems become severe.

Proactive Management

Proactive measures that restore the natural capacity of rivers to buffer climate-change impacts may also lead to other environmental benefits such as higher water quality and restored fish populations. Examples of such measures include stormwater management in developed basins, land acquisition around the river, or levee-setbacks to free the floodplain of infrastructure, absorb floods, and allow regrowth of riparian vegetation (Palmer and others 2008).

While shifting climate regimes may result in local shifts in species assemblages (Thuiller 2004), if there are flora and fauna of special value associated with a river, proactive responses to ensure the persistence of these species are needed and require detailed understanding of species' life histories and ecology. For rivers in regions expected to experience hot, dry periods, establishment of drought-tolerant varieties of plants may help protect the riparian corridor from erosion. A focus on increasing genetic diversity and population size through plantings or via stocking fish may increase the adaptive capacity of species. Aquatic fauna may benefit from an increase in physical habitat heterogeneity in the channel (Brown 2003), and replanting or widening any degraded riparian buffers may protect river fauna in many ways including providing more shade and maintaining sources of allochthonous input (Palmer and others 2005). Australia has experienced numerous, severe droughts and proactive responses have included setting back levees to restore floodplains so they once again store water. As Bond and others (2008) emphasize, rather than regard droughts as extreme events to be responded to when they occur, management practices should be built around the premise that variability in climate that generates variable river flows is not only expected but assumed to be a fundamental trait of natural systems.

At the core of proactive strategies is the ability to *anticipate* change and to *adapt* river management to those changing circumstances. It is important that this adaptive capacity be built at the watershed scale, incorporating activities such as grazing, farming, forestry and other land-uses, reservoir management, water withdrawals, and ensuring minimum environmental flows (Arthington and others 2006). A new layer of cooperation and coordination among land and water managers will thus be essential to the successful implementation of these adaptive strategies (Poff and others 1997, 2002). Currently, legal and institutional barriers to effective management exist in many river systems, and will need to be overcome for the adoption of effective management strategies. Water rights, interstate water compacts, water markets, property rights, and zoning patterns may all present constraints to effective adaptation strategies. Studies of the Colorado River basin, for example, have found that much of the potential economic damage that may result from climate change is attributable to the inflexibility of the Colorado River Compact (Loomis and others 2003). The new stressor of climate change, on top of the existing pressures of population growth, rising living standards, increasing water demands, land-use intensification, and other stressors, may demand a re-evaluation of the institutional mechanisms governing water use and management, with an eye toward increasing flexibility and a stronger consciousness of ecological issues and consequences for rivers and the environmental goods and services they provide.

Place-Based Management

As the previous discussion of proactive and reactive actions reveals, many general recommendations can be made for protecting or repairing negative impacts of climate change. To move beyond generalizations, however, requires a place-based approach built on specific climate changes projections for a region and how these are likely to play out given the local context. We use the word *local* to represent the watershed size (spatial scale) that best matches the scale of management for a region. Some regions will have multiple management scales requiring tiered management strategies. For example, the Colorado River basin in the U.S. encompasses a very large area and at this scale, management of water rights and extractions are critical. Within the larger basin, individual states like Arizona or even subwatersheds in smaller counties or within tribal lands should also consider local strategies to increase protection of river corridors and control development. For each management scale, climate projections in the context of expected changes due to population growth and development are needed. As management strategies are developed, it is important that stakeholders recognize that human needs such as flood or drought protection may not always be consistent with maximizing ecological benefits like enhanced fisheries due to restoration of the historic flow regime.

Place-based management plans can be developed to minimize negative impacts from climate change. In Table 3, we identify six action areas that will contribute substantially to the successful development of plans. First, enhancing water monitoring capabilities and applying local climate forecasting to predict changes will allow jurisdictions to respond most appropriately to their specific local needs. River flow monitoring must be adequate to detect and adapt to flow alterations due to climate change and other stressors all of which may vary from place to place. This may mean installation or re-activation of discharge gauges. If flooding is expected to increase as a consequence of more rapid snow melting in spring, river managers can use flow data along with modeling tools to estimate the acreage and location of additional land conservation easements to pursue, or where to encourage local zoning that limits development on floodplains. Further, the use of models to run scenarios that capture the spectrum of possible outcomes is an invaluable tool for anticipating the ramifications of climate-related hydrological and land-use changes, including reduced snowpack, greater spring flooding, lower summer flows, and warmer stream temperatures. For example, warming trends across the Southwest U.S. exceed global averages by 50%, providing ample evidence of the importance of planning for reduced water availability and streamflows in the Rio Grande and other southwestern U.S. rivers (New Mexico Office of State Engineer and Interstate Stream Commission 2006).

Second, building capacity to offer technical assistance to local managers is critical because many of them do not have the staff or resources (e.g., GIS or modeling capabilities) to undertake forecasting or scenario-building exercises. The ability of managers to demonstrate to communities the importance of certain zoning restrictions, land conservation measures, land-use modifications, or floodplain restrictions may require user-friendly models or tools that exhibit potential climate change impacts within specific watersheds. While sophisticated tools may be feasible to use in regions with ample resources to support management activities, there is a need for affordable tools for areas with fewer resources.

Third, designating more river corridors as protected and/or acquiring and restoring land adjacent to rivers or in their headwaters provide the greatest protection for rivers. Species' extinctions, flood risk, and water shortages will be reduced if the land helps buffer the rivers from nearby development pressures or the land allows for floodplain expansion. Other than privately owned parcels of land that are protected, many local and national governments protect land. In the U.S., rivers or river segments that are officially designated as Wild and Scenic are offered some protection by virtue of a 1979 Presidential directive and in March of 2008, 50 new designations were made bringing the total number protected in this system to 252.

Fourth, the use of conjunctive groundwater/surface water management approaches is highly recommended. The protection of river health and natural flows under a changing climate will require more concerted efforts to determine appropriate environmental flows, namely flows that will support the ecosystem (Arthington and others 2006). For regulated rivers, collaborative arrangements with dam managers offer great potential to secure beneficial flows (Poff 2002; Poff and others 2006) and this could occur by adjusting reservoir release schedules and/or designing structures for temporary storage of flood waters before they reach reservoirs. In regions with extremely high rates of evaporation, managers may wish to work with requisite authorities to consider removing dams associated with shallow, high-surface area reservoirs. In such cases, alternative strategies for water storage or accessing new water sources such as groundwater will be needed. Finally, with large changes in reservoir water levels, the dam outlet height may need adjusting to ensure high quality water to downstream river reaches. The purchase or leasing of water rights to enhance flow management options can also be a valuable tool. For example, the establishment of dry-year option agreements with willing private partners can ensure that flows during droughts remain sufficient to protect critical habitats and maintain water quality. A strengthening of environmental flow programs and water use permit conditions to maintain natural flow conditions will also be critical.

Fifth, restoration prioritization schemes should be developed to repair the most vulnerable river segments. Restoration can be done either proactively to protect existing resources or new projects may be required to repair damage associated with a changing climate. Since floodplains and riparian corridors are critical regions both for mitigating floods and for storing water, measures should be taken to ensure they are as healthy as possible. This could include removal of invasive plants that threaten native species, re-grading river banks to reconnect floodplains to the active channel, and a whole host of other measures that are more fully described elsewhere (Bernhardt and others 2005; Wohl and others 2008; Palmer and others 2008).

Sixth, special attention should be given to protecting, relocating, or creating (if possible) diverse habitat types, habitats types of unique value, or species of special interest. While protecting more rivers and their corridors is essentially an adaptation approach that provides a sort of "replication" of habitats it is also important to protect diverse habitat types and large areas since both should

Table 3 The development of place-based management plans to minimize the negative impacts of climate change on river ecosystems requires specific actions at the spatial scale most appropriate for local river management; each of the six suggested actions below are more fully explained in the text

Place-based adaptation actions	Explanation
1. *Enhance local monitoring and develop forecasts*	To facilitate planning and prioritization of adaptation options and to allow for reactive responses to any negative impacts of climate change, river discharge and conditions must be monitored regularly. Regional forecasts are needed to better understand the local effects of climate change.
2. *Enhance technical assistance at local levels*	Most management is implemented at local levels where technical capacity (e.g., personnel, planning, modeling tools) is typically insufficient to meet expanding needs.
3. *Enhance protection of rivers*	
Acquire land and expand protected areas	Returning land to more vegetated state and protecting wild regions of watersheds will increase natural adaptive capacity of river ecosystems. Designating more rivers or river segments as protected provides replication in space of at-risk habitats and provides refugia for species.
Enhance stormwater control, wetland creation, and floodplain management	Increased infiltration (stormwater infrastructure) and water storage in wetlands and floodplains will minimize floods and conserve water for future use.
Manage riparian corridors	Protection of riparian vegetation is critical to river biota and biogeochemical processes. Re-planting (and potentially re-grading under extreme conditions) may be required reactively if flooding or droughts cause high plant mortality.
4. *Use conjunctive groundwater/surface water management*	
Drought protection actions	Purchasing more water rights, designing water storage structures and/or developing methods to divert water to groundwater storage may be needed if droughts are expected.
Retrofit or remove dams	If projected increase in discharge can not be handled by only increasing reservoir releases, consider removing dams at high risk of failure or fortifying dams to store excess water, sediment and pollutant loads in reservoirs. If droughts are projected, dam removal may be needed below shallow reservoirs in areas of high evaporation; however, if dams are left intact, elevation of the outlet that releases reservoir water to the downstream river may need moving to ensure delivery high water quality.
Sustain environmental flows	Reservoir releases can be altered not only to store and release water to avoid/abate floods and risk of dam failure but the timing and magnitude of releases can be set to mimic historic (ecological) flow regimes as close as possible. If droughts are projected, releases will need to provide environmental flows downstream and restrictions on extractions may be necessary to protect river ecosystems.
5. *Initiate Restoration Projects*	
Stabilize banks or reconfigure channels if required	Channel alterations may be necessary as a reactive measure if floods cause bank failure or large-scale geomorphic adjustments pose risk to humans.
Ensure fish passage	Reactive measures may be needed in regions with migratory aquatic species if climate change leads to fragmentation of river segments.
Reconnect floodplains	Floodplains that are disconnected from rivers by levees, infrastructure, or incised channels can be proactively re-connected to protect riparian ecosystems. Intact floodplains will allow overbank flows that are critical to biota and biogeochemical processes and that enhance groundwater recharge.
Complete habitat improvements	Habitat rehabilitation in river channels may be necessary as a reactive measure if floods occur or dramatically lower water levels cause habitat degradation.
6. *Diversify and replicate habitats and populations*	
Replicate habitat protection across space	Protecting habitats of the same type in multiple locations reduces the risk of total loss of species common in those habitats.
Protect some areas large enough to capture diverse habitat types	Larger areas are associated with higher species diversity. Some species may shift their habitat preferences under future climates and ability to move across a range of habitats may enhance their persistence.
Monitor and manage species of interest	Biological monitoring can be used for early detection of changes in reproductive output or population size. Populations that become vulnerable may be candidates for experimental translocation of individuals to other regions.

provide insurance against large-scale extinctions. There is a well-known relationship between land or watershed area and species diversity; as area increases, the probability of including different habitat types also increases (Angermeier and Scholosser 1989; Amarasinghe and Welcomme 2002). Spreading these adaptation efforts spatially is important because habitats of the same type (e.g., U.S. mid-Atlantic Piedmont riparian wetland) but in different locations (e.g., North Carolina versus Virginia) may be differentially impacted by climate change because of their local context (e.g., riparian wetland with modest development nearby versus riparian wetland influenced by water releases from upstream reservoirs). This spreads the risk of losing unique species because habitats in locations that fare well over time may provide refugia (across space) even if others experience extirpations. For species of special interest, careful monitoring of population sizes and their health can alert managers to take actions before species are at risk.

Conclusions

Rivers and the ecosystem services they provide are increasingly at risk due to land-use changes, population growth, pollution discharges, flow-regime alterations by dams and diversions, and excessive groundwater pumping. Predicted climate change can add to and magnify these risks through its potential to alter rainfall, temperature, and runoff patterns, as well as to disrupt biological communities and sever ecological linkages in any given locale. The anticipation of climate change impacts requires a proactive management response if valuable river assets are to be protected and a proactive response requires sound monitoring and predicting capabilities at the scales that management actions can be applied—this is almost always at the local watershed scale. Unfortunately, many jurisdictions do not have the resources to implement such programs, particularly in developing countries. Yet waiting to respond reactively will be more expensive (Palmer and others 2008) and may result in species losses and injury to people. Thus national and international funding programs need to be established to provide the tools, training, and financial resources to support proactive place-based management actions.

Given limited financial and human resources, the highest management priorities for the protection of river assets under conditions of climatic change include: acquiring adequate baseline information on water flows and water quality to enable river managers to prioritize actions and evaluate their effectiveness, developing comprehensive scenarios of the likely impacts of climate change in specific watersheds (i.e., forecasts that apply to specific rivers given local land use and water use contexts are needed), developing mechanisms for establishing collaborative relationships that are essential to implementation of adaptive river management strategies, ensuring environmental flows and minimizing the development of parcels of land adjacent to highly valued rivers. Restoring or increasing protection of floodplains and riparian corridors will not only provide protection for river ecosystems but it will reduce the impacts of both floods and droughts on people that rely on rivers for their water. Removing infrastructure along rivers to accomplish these objectives may seem drastic but in the long run ecosystems and people may be spared harm. Finally, giving more watersheds protected area status—particularly those at high elevations or in regions expected to experience the most dramatic climate changes—will help to provide refuge habitat for many species threatened by climate change and other threatening processes.

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