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Freshwater conservation options for a changing climate in California's Sierra Nevada

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Abstract. Catchments of California's Sierra Nevada have been managed for hydropower, water supply, recreation and the environment, during which regional freshwater ecosystems have experienced extirpations of anadromous fishes, widespread loss in amphibian abundance and increases in non-native species. California's Mediterranean-montane climate is expected to warm by 2–6°C over the next century, reducing snowpack, causing earlier runoff and altering flows. Freshwater conservation efforts currently rely on a patchwork of legal and regulatory mechanisms, and have failed to achieve their full potential because of weak and uncoordinated implementation. No scheme adequately addresses freshwater conservation objectives such as representation and persistence, and all ignore anticipated impacts of climate change. We recommend that (1) existing legislation be fully implemented, with explicit anticipation of future conditions, (2) local institutions develop and implement a systematic freshwater conservation plan, focusing on resilience to climate warming, (3) policies be crafted to prioritise catchments to emphasise key regional objectives (e.g. conservation) and (4) regional planning agencies with regulatory authority be formed at the catchment level.

Additional keywords: California, climate warming, freshwater conservation, Sierra Nevada, water management.

Introduction

Increasing demands placed on global water resources for people (Vörösmarty *et al*. 2000) have led to dramatic declines in freshwater biodiversity and increased the need for systematic freshwater conservation planning to protect remaining biodiversity and sustain ecosystem services (Dudgeon *et al*. 2006). As Earth's atmosphere warms in the coming century, water resources will be affected by changes to the timing, magnitude, frequency and form of precipitation (Bates *et al*. 2008). The freshwater ecosystems of Mediterranean-montane ecoregions, found in Australia, California and South Africa, will be further stressed, as a result of a shortened rainy season and prolonged, warmer summer season (Klausmeyer and Shaw 2009). The combined importance of freshwater and Mediterranean habitats to global biodiversity underscores the importance of effective freshwater conservation in the Mediterranean biome (Sala *et al*. 2000), which is imperilled by many anthropogenic stressors, including agriculture, urbanisation and invasive non-native species (Underwood *et al*. 2009).

In the future, aquatic ecosystems of the Mediterranean biome, characterised by biotic responses to highly seasonal yet predictable flow events, are likely to be highly vulnerable to non-stationary long-term changes in hydrologic regime (Milly *et al*. 2008). Anticipated changes to the snowmelt recession in montane regions of the Mediterranean may further disrupt seasonal cues and alter abiotic processes, critical to maintaining ecological fluxes (Yarnell *et al*. 2010). As such, freshwater biodiversity conservation will need to be prioritised within management schemes to be effective, because adaptation to changing hydroclimatic conditions by water managers will likely be *ad hoc* and reactionary (Viers 2011), leaving few opportunities for systematic conservation planning across broad areas.

Symptomatic of these challenges in conserving freshwater ecosystems of the Mediterranean biome, the catchments of California's Sierra Nevada mountain range are at the nexus of changing hydroclimatic conditions (Tanaka *et al*. 2006; Maurer *et al*. 2007; Medellin-Azuara *et al*. 2008; Young *et al*. 2009) and human-degraded freshwater habitats (Marchetti *et al*. 2004; Light and Marchetti 2007; Moyle *et al*. 2008), and form the core of a global biodiversity hot spot (Thorne *et al*. 2009). We describe the current freshwater conservation framework in California's Sierra Nevada and review promising freshwater conservation options with a changing climate. We also recommend regulatory and management strategies for better freshwater biodiversity conservation for resource managers in other catchments of the Mediterranean biome, where conservation targets are often sensitive to flow regimes and the anticipated effects of climate change will require adaptation strategies (Hermoso and Clavero 2011).

Environmental setting

The Sierra Nevada mountain range, in eastern California (Fig. 1) and western Nevada (USA), is characterised by its bedrock-dominated fluvial system, created largely by granitic uplift

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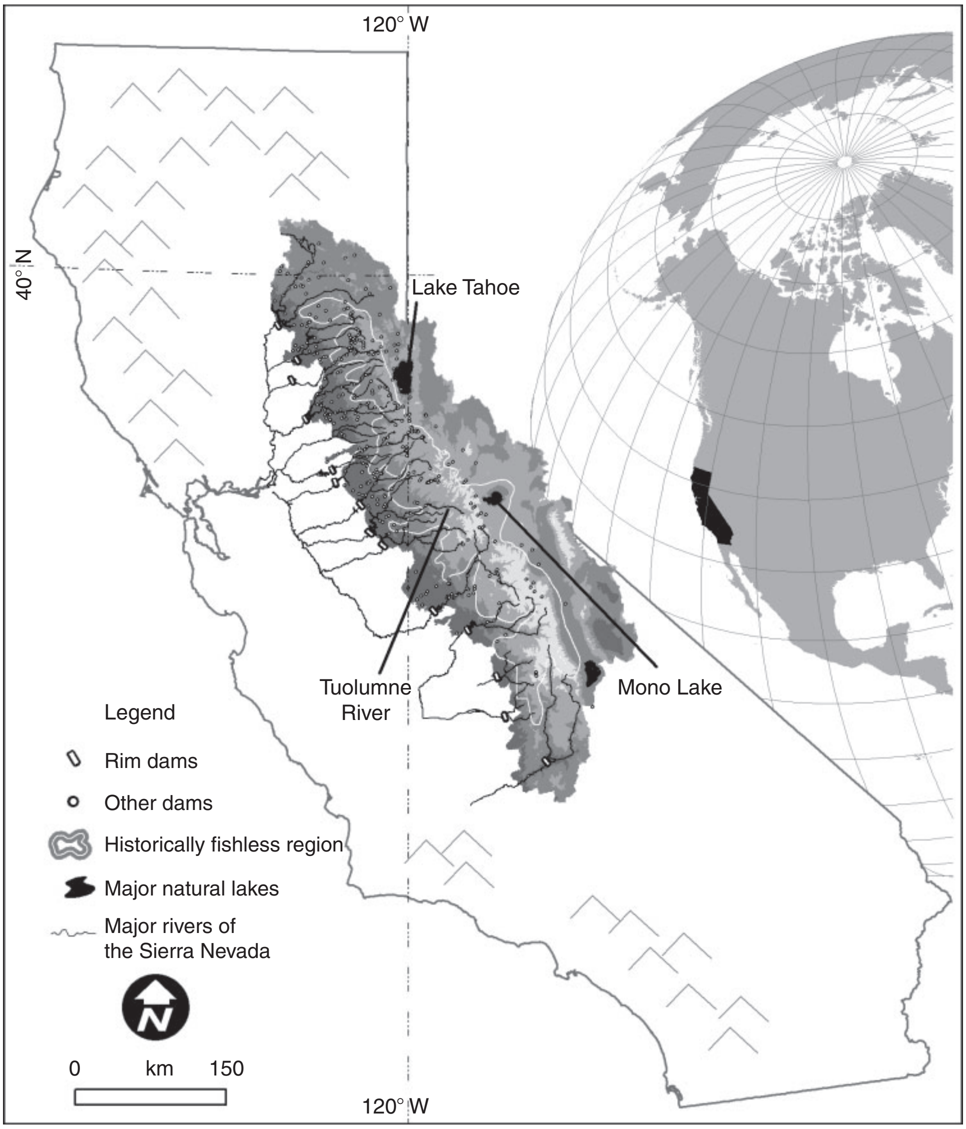

Fig. 1. Map of Sierra Nevada (California, USA), showing prominent rivers and dams.

along its 650-km length, from near sea level (~100 m) to peak elevations 4000+ m in the south and to 2500+ m in the north. The western slopes of the range rise more gradually than the steep slopes of the eastern side. Because of the proximity of the Pacific Ocean and orographic precipitation, it receives ample precipitation (~2000 mm year^{-1}), mostly during the cold winter months, consistent with a Mediterranean climate. Highly variable rain-driven winter flows are followed by snowmelt flows that predictably gradually decrease from spring into mid- or late summer. During the summer low-flow period, baseflows are largely hyporheic and warm, with air temperatures often exceeding 40°C at low elevations.

Fifteen major drainage basins on the western slope of the Sierra Nevada, from the Feather River basin in the north to the Kern River basin in the south, drain 26.2×10^9 m^3 per year on average (1981–2001), from 47 700 km^2 (Null *et al*. 2010). These basins contribute ~30% of California's total annual runoff and most of the water diverted for use in California's Central Valley, one of the most agriculturally productive regions in the world. Fourteen major flood-control and water-supply dams ('rim' dams) separate most of the Sierra Nevada's aquatic ecosystems from the lowland Central Valley (Fig. 1). Water upstream of these dams is managed mostly for hydropower and water supply. Management infrastructure includes 126 dams larger than 1000 acre-feet (1.23×10^6 m^3), which have a collective storage capacity of 24.6×10^9 m^3 or 94% of the annual runoff, 134 hydropower facilities (8800-MW collective capacity) and supporting conveyances (Null *et al*. 2010). Although the eastern Sierra Nevada is far more xeric, as a result of the rain shadow effect of the range, much of its water is expropriated out of six major endorheic basins, and many of its high-relief rivers are developed for hydropower. This extensive development of water resources is characteristic of many river systems in the Mediterranean biome, where the timing of freshwater supply (i.e. precipitation) is often asynchronous with demand (Grantham *et al*. 2010).

Status of freshwater biodiversity

The fauna of Sierra Nevada streams, part of the greater Sacramento–San Joaquin ecoregion (see 'Pacific Central Valley' in Abell 2000), are representative of Mediterranean freshwater systems where most lotic organisms have life-history traits that exploit periods of favourability, or conversely, provide resistance to extreme variability in flow conditions (i.e. floods and droughts) (Grantham *et al*. 2010). Indicative of California's zoogeography and relative freshwater isolation, the Sierra Nevada harbours many endemic species of aquatic organisms, and nearly as many genera as species of fishes (Moyle 2002). Broadly, these species have adapted to a Mediterranean-montane flow regime of episodic high flows during the wet, winter season with disturbance-driven abiotic stresses, static low-flow conditions during the dry season with competition-driven biotic stresses, and predictable vernal snowmelt recession flows that serve as windows of opportunity for population expansion and recruitment (Gasith and Resh 1999; Yarnell *et al*. 2010).

As is the case in other Mediterranean freshwater ecosystems (Bonada *et al*. 2007*b*, 2008), macroinvertebrates are robust indicators of water quality and representative of environmental constraints on freshwater biodiversity. Despite their recognised ecological importance, and use in bioassessment of water quality (Herbst and Silldorff 2006), macroinvertebrates have not been comprehensively studied throughout the Sierra Nevada range. Aside from a synthesis (Erman 1996), the only range-wide assessment was conducted by state and federal water-quality authorities as part of a broad survey (Stoddard 2005), and used only 81 sites to characterise the entire range (87 500 km^2). Rehn (2009) recently completed a comparative study of hydrologically altered catchments and unregulated reference sites; however, most studies have been more localised and focussed on unique species (e.g. Bartolome *et al*. 1990), which is reflective of Mediterranean freshwater ecosystems high in taxonomic diversity (Bonada *et al*. 2007*a*).

The western Sierra Nevada has the following three main freshwater fish assemblages, which serve as proxies for trophic food webs: rainbow trout, California roach and pikeminnow–hardhead–sucker (Moyle 2002). Although listed from highest to lowest elevation in distribution, there is a significant overlap among assemblages. Their distributions differ primarily by habitat type and environmental conditions such as hydrologic regime, geomorphology, food availability and water quality (e.g. temperature). The eastern Sierra Nevada is almost exclusively a rainbow trout (*Oncorhynchus mykiss*) assemblage, with congeneric representation by cutthroat trout (*O. clarki henshawi*). Rivers and streams above ~1500 m were historically fishless because of repeated glaciation, most recently in the late Holocene (>10 000 years before present) (Clark and Gillespie 1997), although an exception is the Kern River, a catchment at the southern end of the range that was unglaciated, the upper reaches of which support endemic golden trout (*O. mykiss aguabonita*), California's state fish. Before recent modifications by humans, the rainbow trout assemblage occupied cold, high-elevation and high-gradient streams. The other assemblages span narrow low-elevation zones in small tributaries, just above the valley floor. It is these low-elevation assemblages that often harbour unique endemic species, such as the rare endemic cyprinid Red Hills roach (*Lavinia symmetricus*) (Jones *et al*. 2002).

Today, the majority of fish species in this region are non-native and nearly 67% of these species are purposefully stocked (Marchetti *et al*. 2004). Introductions of hatchery-bred rainbow trout have expanded the range and viability of the rainbow trout assemblage, primarily into the historically fishless high-elevation lakes and streams, but not without consequences. Recent studies have documented trophic cascades affecting secondary production and diversity in alpine freshwaters (Herbst *et al*. 2009), as well as the riparian bird community (Epanchin *et al*. 2011). There is decline of native and endemic amphibians, once broadly distributed throughout the range although restricted to specific elevation bands (Jennings and Hayes 1994). Throughout the Sierra Nevada, this drastic decline is due to many interrelated factors, most conclusively the introduction of trout to previously fishless amphibian habitats (Knapp *et al*. 2001), including protected areas (Knapp and Matthews 2000). Other factors contributing to their decline include range-wide habitat fragmentation (Jennings and Hayes 1994), widespread invasion of non-native American bullfrogs (*Rana catesbeiana*) (Jennings 1996), pesticide drift from the Central Valley (Davidson 2004; Davidson and Knapp 2007) and local urbanisation (Davidson *et al*. 2001). In addition to endemic salamanders considered California Species of Special Concern (e.g. Mt Lyell salamander, *Hydromantes platycephalus*), populations of the foothill yellow-legged frog (*Rana boylii*) found in the foothill and Yosemite toad (*Bufo canorous*) found at high elevation are similarly diminished. The California red-legged frog (*Rana aurora draytonii*) is listed under the federal *Endangered Species Act* as Threatened, and the Sierra Nevada yellow-legged frog (*Rana sierrae*) was also deemed threatened although it was not listed because of insufficient resources. Successful long-term freshwater conservation efforts are imperative, because only one native amphibian, Pacific chorus frog (*Pseudachris regilla*), is considered to have stable populations.

The most pervasive change to the freshwater ecosystems of the Sierra Nevada is the near-complete elimination of anadromous salmonids, foremost the large-bodied chinook salmon (*O. tshawytscha*). They form genetically differentiated metapopulations occupying natal spawning grounds, and exhibit up to four seasonally asynchronous life histories in a given catchment. Chinook salmon runs of California's interior basins (i.e. Sierra Nevada) were historically some of the most productive runs on the Pacific coast of North America (Yoshiyama *et al*. 1998). Today, most Sacramento–San Joaquin Valley runs of chinook salmon and steelhead (anadromous form of *O. mykiss*) are extirpated from the Sierra Nevada streams, because of blockage of migratory pathways to spawning grounds by large rim dams (Yoshiyama *et al*. 1998; Moyle 2002). The few remaining runs in the Sierra Nevada are in small low-elevation tributaries of the Sacramento River without large dams, although some extant runs do exist below rim dams on the valley floor and are mostly perpetuated by hatchery production. These extirpations did not only change the faunal composition of freshwater ecosystems, but also eliminated a massive marine-derived nutrient subsidy to aquatic and riparian food webs (Janetski *et al*. 2009).

Threats to freshwater biodiversity

Although the impacts of human development activities on the aquatic ecosystems of the Sierra Nevada are generally well known (e.g. Allan and Flecker 1993), few range-wide assessments of threats to freshwater biodiversity exist. Here, we identify the major impacts from historical and contemporary management, and potential threats from hydroclimatic change.

Since the discovery of gold in the Sierra Nevada in 1848, and the subsequent rapid influx of fortune seekers during the California Gold Rush, land and water development has severely altered freshwater ecosystems. Resource extraction includes gold mining, timber harvesting, sheep and cattle grazing, water abstractions, and damming of rivers for hydropower, water supply and flood control (Mount 1995). Early impacts (pre-1900) to rivers and streams were primarily sediment loading from hydraulic mining and erosion by livestock grazing and logging, which degraded or eliminated fish spawning habitat (Moyle 2002). Between 1900 and 1950, extensive water development for downstream agricultural supply and hydropower via dams and diversions had the following two main impacts on freshwater fauna, particularly anadromous salmonids: (1) blockage of migratory pathways eliminated access to spawning habitat; and (2) alteration of the natural flow regime disrupted seasonal cues and exacerbated less favourable environmental conditions. The land and water management schemes, from 1950 to 2000, largely compounded degradation of habitats. For example, grazing and timber harvest, promoted on US Forest Service (USFS) lands, exacerbates the mobilisation of a legacy of mercury contamination from mining into rivers and streams in northern Sierra Nevada catchments (Alpers *et al.* 2005), ultimately promoting bioaccumulation in a variety of organisms (Suchanek *et al*. 2008). The combined effect of habitat degradation and fragmentation and altered flow regimes has made much of the Sierra Nevada prone to homogenisation of its fish fauna (Marchetti *et al*. 2004), largely fuelled by widespread and purposeful introductions of non-native fish species by resource management agencies.

A 'watershed' index quantified Sierra Nevada-wide effects of impacts on biotic integrity at the catchment scale (Moyle and Randall 1998). The catchments with the highest biotic integrity for fish and amphibian assemblages were small, inaccessible catchments with low development potential and some intermediate scale tributaries. Conversely, catchments with low integrity included low- to middle-elevation drainages with numerous dams and diversions, high-elevation catchments, where stocked, non-native trout have replaced native frogs or low-elevation catchments with extensive local urbanisation and other development.

Anticipated climate-change impacts

Globally, climate warming is anticipated to affect Mediterranean-montane hydroclimatic systems by altering the spatial and temporal distribution, intensities and extremes of precipitation (Klausmeyer and Shaw 2009). In their global analysis, Milliman *et al*. (2008) showed that hydrologic basins in the Mediterranean biome had experienced significant reduction in discharge between 1951 and 2000, uncorrelated with trends in precipitation. Regional variability in annual precipitation, highly correlated with global ocean currents (Hertig and Jacobeit 2010), will probably dominate the hydrologic response (Grantham *et al*. 2010) in Mediterranean-montane rivers.

In California, the climate is expected to warm by 2–6°C over the next 50–100 years (Hayhoe *et al*. 2004), which will reduce winter precipitation stored as snow (Vicuna and Dracup 2007; Young *et al*. 2009). Less storage as snow will increase the frequency and magnitude of rain-driven flow events and cause earlier snowmelt, resulting in earlier runoff and reduced spring and summer flows. Increased temperatures will also increase evapotranspiration, reducing flows overall, particularly during the summer (Young *et al*. 2009). Snowmelt runoff in North America is already occurring earlier (Stewart *et al*. 2005; Maurer 2007) and annual runoff in California's large rivers has been decreasing (Dettinger *et al*. 2004; Anderson *et al*. 2008). Although climate models consistently predict warmer average annual temperatures in California, there is little consensus about the change in the magnitude and timing of precipitation. Averaging climate models results in little, if any, change in precipitation, with most precipitation still occurring during the cold winter months, reinforcing the perception of a continued Mediterranean climate (Dettinger *et al*. 2004).

As surface air temperatures warm, stream temperatures are expected to rise, because of their strong positive correlation (Morrill *et al*. 2005). This alteration will exacerbate environmental stresses to freshwater ecosystems when combined with altered natural hydrologic regimes (Quesne *et al*. 2010). Cascading direct, indirect and interactive effects of rising stream temperatures, such as reductions in dissolved oxygen or disruption of reproductive cues (Caissie 2006), are likely to redefine the spatial distribution of ecotopes (*sensu* Whittaker *et al*. 1973). Species dependent on stream-temperature thresholds are expected to shift in elevation (Carpenter *et al*. 1992), whereas species with volumetric niche requirements (e.g. seasonal floodplain access) are likely to fragment as a result of spatial and temporal discontinuities in the flow regime. For the in-stream biota of the Mediterranean biome, the seasonal interaction of increased stream temperatures and reduced baseflows during summer months will be stressful and may alter the composition of native communities or further encourage faunal homogenisation by invasive species. In the Sierra Nevada, the most likely result of increased stream temperatures will be range compaction of rainbow trout. Physiologically stressful conditions will limit low-elevation persistence, whereas dispersal will be limited by natural topographic barriers at high elevations in unregulated rivers and streams.

Although the magnitude of the potential change is unknown, we discuss likely changes, and their potential cascading effects from ecohydrological principles (Table 1), similar to anticipated global changes (Palmer *et al*. 2009; Quesne *et al*. 2010). These cascading effects are directly and indirectly tied to changes in the magnitude, timing, frequency, duration and rate of change in discharge and, importantly for the Sierra Nevada, melting snowpack. We anticipate that an overall reduction in the annual runoff will change habitat quality, with concomitant shifts in species' assemblages (Table 1). Additional changes to hydrological function, such as the rate of snowmelt recession, will alter disturbance regimes, with cascading effects on channel-forming processes (Yarnell *et al*. 2010), meadow recharge and,

Table 1. Potential changes to flow regime caused by climate warming-mediated hydrologic alteration, with potential cascading ecosystem effects

Potential Change	Cause	Potential cascading effect
1. Annual stream flow reduced	Changed precipitation timing and form (i.e. less snow, more rain); increased stream flow losses with increased evapotranspiration	Reduced habitats (i.e. niche space) of all aquatic species; increased water temperature; decreased dissolved oxygen; increased riparian plant stress via desiccation and disease; shifted species' distributions
2. Reduced rate of snowmelt recession (see Yarnell *et al.* 2010)	Increased separation between the peak snowmelt period and the initiation of low-flow season (via increased duration) and decreased snowmelt magnitude	Decreased frequency and magnitude of disturbance; increased riparian establishment where substrate and hyporheic flows allow channel hardening; shift in invertebrate community; reduced seasonal floodplain habitat, spawning and rearing habitat; shift in vertebrate community
3. Contraction and loss of meadows and wetlands	Loss of snow (and recharge) lowering watertable; increased upland vegetation encroachment and subsequent losses of stream flow to increased evapotranspiration	Increased erosion and sediment load as a result of incision; increased flashiness downstream; reduced base flows in summer
4. Reduced base flow in summer	Shifted timing of centre of annual hydrograph; earlier onset of snowmelt recession	Reduction in physical habitat; increased water temperature; decreased dissolved oxygen; increased physiological stress in some animals; increased riparian plant stress via desiccation and disease; increased susceptibility to catastrophic fire

ultimately, increased susceptibility of plant communities to disease and catastrophic fire (Table 1).

Existing freshwater conservation efforts

Freshwater conservation efforts in California can be legal-, policy- or science-based (Viers 2008), although most legal and policy frameworks rely on some science. There is no single legal or regulatory organisation or mechanism that drives management. Further, there is no single entity responsible for conservation of freshwater biodiversity or any approach that explicitly incorporates adaptation to climate change. Various laws and regulations compel active freshwater ecosystem management by an authority or provide a framework for stakeholders to agree to a management scheme. We recommend changes on the basis of a review of the key laws, regulations and policies for freshwater conservation in the Sierra Nevada. We do not discuss the numerous federal, state and local laws and regulations that apply to specific resource management that affects freshwater ecosystems (e.g. permitting stream-bed alteration). Further, it is important to recognise that state- or national-level legal and regulatory frameworks are often limited in spatial scope by land or project ownership or in functional scope by specific natural resource or species, and none addresses freshwater ecosystem conservation issues.

Environmental laws

There are four principal federal laws that form the basis for regulatory management and conservation of freshwater biodiversity in the Sierra Nevada (Table 2). Each has a corresponding state law that is often more stringent. The *National Environmental Policy Act* (*NEPA*) is the most important, compelling all federal agencies to consider impacts on the environment by direct (e.g. building a dam) and indirect (e.g. a dam-building permit) actions. Federal agencies must formally consider a range of management alternatives and potential impacts; however, they can still choose an environmentally damaging one. The *California Environmental Quality Act* (*CEQA*) stipulates that state agencies can proceed only with the most detrimental action if all mitigation measures and alternatives, including a 'no project' alternative, are not feasible.

The federal *Clean Water Act* (*CWA*), and its state counterpart, can enforce water-quality standards via certification of water-quality measures and the development of quantitative loads for non-point source pollutants. Certification can be enforced by fines and 'cease and desist' orders. Despite this capability, water-quality managers prefer cooperative approaches to improvement, with little evidence as to their effectiveness (Little Hoover Commission 2009).

The federal and state versions of the *Endangered Species Act* (*ESA*) are perhaps the most feared environmental laws, and also laws of last resort; their stringent requirements to abate harm (i.e. 'no take' provisions) are enacted only once a species extinction is imminent. They provide opportunities for freshwater biodiversity conservation through identification of critical habitat for species recovery (Viers 2008), and Habitat Conservation Plans (HCPs) permit landholder activities in exchange for measures of habitat protection (Bricker and Filippi 2000). Unfortunately, the *ESA* does not address biodiversity objectives

Table 2. Key environmental laws of USA and California, relevant to freshwater conservation in Sierra Nevada

Environmental law	Purpose	Implementation
Clean Water Act (1972, amended 1987) / *Porter-Cologne Act* (1969, amended 2010)	Sets qualitative and quantitative water-quality standards to protect beneficial uses in waterbodies (estuaries, groundwaters, lakes, rivers and streams); monitored and enforced by both federal and state Environmental Protection Agency	Beneficial-use determination and standards is delegated to states; California delegates responsibility to nine Regional Water Quality Control Boards; regional boards designate waterbodies and develop 'basin plan' for water-quality targets
Endangered Species Act (1972, amended 1982) / *California Endangered Species Act* (1984, amended 1991)	Prevent species extinction and recover imperilled species; designations of 'Threatened' or 'Endangered' can apply to species or an evolutionarily unique population within a species; identification and designation of 'critical habitat' to recovery is explicitly included; designations invoke actions to prevent further 'take' or species loss	Requires development and implementation of recovery plans; requires designation of critical habitat for recovery; habitat conservation plans (federal) or natural communities conservation plans (state) can be developed to encourage private landowner cooperation in species management or habitat protection; 'Safe Harbor' agreements can hold private parties harmless (i.e. not liable) for incidental taking of species as a result of voluntary actions to conserve or improve habitat
National Environmental Policy Act (1969, amended 1982) / *California Environmental Quality Act* (1970)	Ensure that federal/state-funded actions consider the effects of the action on the environment into the reasonable and foreseeable future	Federal and state agencies that fund, implement or issue permits or licences for projects must document the environmental impacts from proposed actions and articulate a range of alternative actions; chosen alternative action may be most detrimental to environment after federal inquiry; chosen alternative action may be most detrimental to environment from state inquiry only if all mitigation measures and alternatives, including a 'no project' alternative, are not feasible
Wild and Scenic Rivers Act (1968, amended 2009) / *California Wild and Scenic Rivers Act* (1972)	Provide varying levels of protection for designated rivers, primarily for recreation and aesthetic values	Managed with a mix of government regulations and programs, river-user practices and riparian landowner stewardship; seven federal-designated and six state-designated rivers/reaches in the Sierra Nevada

or even causes of population decline at the catchment scale (Moyle 1996).

By their titles, the federal *Wild and Scenic Rivers Act* and its state counterpart would appear best-suited environmental laws for protecting freshwater biodiversity in rivers and streams, with the goal of protecting and enhancing the values that spurred a river's designation. However, designation of a wild and scenic river status neither prohibits development nor gives the government control over private property. Pre-existing activities such as recreation, agricultural practices, residential development and other streamside and extractive uses may continue. Future activities can continue as long as they do not affect designation of wild, recreational or scenic, each with separate thresholds of determination. Protection of rivers is largely through voluntary stewardship by landowners and river users and other regulations (e.g. *NEPA*, *CWA*, *ESA*) and programs of federal, state, local or tribal governments. In practice, wild and scenic status affords little additional protection to rivers, although it can prevent major developments, such as hydropower schemes, if the action alters a river's designated character.

Public Trust Doctrine

Conservation of freshwater ecosystems is intimately tied to water rights in California. Water rights determine where, when and how water is used, including flows for freshwater fauna. California water rights law is complicated, but follows a few basic principles. There are appropriative (off-stream) and riparian rights to surface water, whereas the state does not regulate groundwater. Appropriative water rights are permitted by the State Water Resources Control Board (SWRCB), whereas riparian or stream-adjacent rights do not require permits. All water uses must be 'beneficial' and 'reasonable' as per the state's constitution, and the underlying California Gold Rush principles of 'first in time, first in right' and 'use it, or lose it' still carry in court today. However, reinterpretation of other legal precedents has altered the legal framework of California water rights.

Founded on Justinian law, the Public Trust Doctrine effectively states that common resources such as air and water are immutable to humankind. The Public Trust Doctrine was largely subsumed by appropriative water rights under California water law until its interpretation in the dispute over water from Mono Lake in *National Audubon Society et al. v. The Superior Court of Alpine County et al.* (17 February 1983). The California Supreme Court reversed a lower court decision and held that the state was sovereign in its responsibility to oversee the use of public resources in the public interests (Blumm and Schwartz 1995). The SWRCB had to consider the public's immutable resource rights when appropriating water for Los Angeles, including the viability of shorebird populations of Mono Lake (Fig. 1), jeopardised by dewatering, despite the prior appropriation. Furthermore, SWRCB has the authority to update and revoke appropriations on the basis of such evaluations. This court decision and others provided the underlying legal rationale for the modern Public Trust Doctrine. This doctrine and associated water rights laws do not explicitly address broad freshwater conservation (e.g. genetic diversity); however, they form the basis for most regulation to conserve freshwater biodiversity in the Sierra Nevada. For example, California Department of Water Resources, which supplies water and supports the development of water resources, now actively emphasises adhering to public trust principles (DWR 2005).

Integrated Regional Water Management Plans

California Department of Water Resources also promotes and funds State Integrated Regional Water Management Plans (IRWMP) (DWR 2005), similar to global integrated water resource management (UN-Water 2008; Banuri 2009). The main goal of an IRWMP is to integrate the planning and management of water resources at the regional scale, explicitly recognising the interconnectedness of water resources. Six plans exist in the western Sierra Nevada, covering the northern half of the range (plans for other locations are under development). An IRWMP, developed by regional water managers and stakeholders, (e.g. water agencies, conservation groups, irrigation districts, local governments), includes short- and long-term goals and objectives, resource characteristics and management strategies (DWR 2005). Although IRWMPs do not legally compel resource managers, they provide coordination of communication for any managers and stakeholders. Shared water governance offers some regulatory responsibility. For example, the Tahoe Regional Planning Authority (TRPA), created in 1980 by the US Congress, is a bi-state compact between California and Nevada, charged with authorisation, regulation, coordination and monitoring of land, air and water uses throughout the Lake Tahoe Basin (Fig. 1). TRPA has been largely credited with enacting changes in land use practices that are credited with stemming the deterioration of the Sierra Nevada's Lake Tahoe.

Hydropower licensing

The Federal Energy Regulatory Commission (FERC), under the *Federal Power Act* (*FPA*), licenses non-federal hydropower projects and rivers in Sierra Nevada. Each FERC licence explicitly defines operating requirements for 30–50 years. FERC is required to give 'equal consideration to the purposes of enhancement of fish and wildlife (including related spawning grounds and habitat)' and, comply with *NEPA*, *CWA* and *ESA* (Table 2). Project owners and stakeholders, including non-governmental organisations (NGOs), various local agencies and citizens, can negotiate the terms of the new licence via an outside settlement agreement. This may incorporate ecologically beneficial flows and other mitigation actions. Government agencies and NGOs for freshwater biodiversity conservation could use this process in the absence of formal regional-scale framework.

Freshwater conservation planning

Protected areas in the Sierra Nevada have existed since the deeding of the Yosemite Grant in 1864; however, freshwater biodiversity conservation was never considered in the establishment of its National Parks or Wilderness Areas. Geological (e.g. Lassen Volcanic National Park) or terrestrial (e.g. Sequoia National Park) merits were primary reasons for protection, although Yosemite's spectacular waterfalls were possibly an aesthetic consideration. The Sierra Nevada is highly emblematic of traditional protected areas inadequately protecting freshwater biodiversity (Abell 2002). Or, as is the case with Yosemite, the protected area contributes to the expropriation of freshwater resources to the City of San Francisco via dams and the Hetch Hetchy Aqueduct (Null and Lund 2006). This is not to say that the current protected-area configuration is unsuitable for freshwater biodiversity, although this is unknown (*sensu* Roux *et al*. 2008). Future strategic conservation of freshwater biodiversity in the Sierra Nevada will require a region-scale vision underpinning systematic freshwater conservation planning (Abell *et al*. 2007). Although several have attempted to identify catchments of high biological value and proposed freshwater conservation strategies for the Sierra Nevada (Moyle 1996; Moyle and Randall 1998), there is currently no formal freshwater conservation network or strategy, with land ownership and land management largely dictating opportunities.

Land ownership and land-use management

Conservation of the freshwater ecosystems of the Sierra Nevada largely depends on land-management schemes, although some rivers are protected explicitly with designation of a Wild and Scenic status (Table 2). Land ownership in the Sierra Nevada primarily consists of National Parks and Monuments, managed for their wilderness and recreation value, Wilderness Areas, managed for their undeveloped nature, other federal lands, such as National Forests and lands of the US Bureau of Land Management, which are managed mostly for timber, grazing and mining, and private lands. There are only small areas of state-owned lands in the Sierra Nevada, such as State Parks. Land ownership and management are highly complex. For example, the Tuolumne River catchment in the Sierra Nevada has extractive infrastructure (e.g. dams and aqueducts) overlying public lands and protected areas (Fig. 2). The Sierra Nevada's protected areas (i.e. parks, wilderness areas and reserves) are almost exclusively located at high elevations and are managed for wilderness values and recreation, including annual fish stocking for angling, which can conflict with conservation targets, such as amphibians (Fig. 2). Understanding the spatial organisation of land management within a catchment is the first step in systematic freshwater conservation (Nel *et al*. 2009, 2011). There are several sophisticated land-use and conservation studies for the Sierra Nevada (e.g. Davis *et al*. 2006; Shilling and Girvetz 2007). The next step of determining the diversity and spatial distribution of freshwater organisms is not well progressed, limiting the development of a conservation strategy.

Catchment prioritisation

There is a need to identify areas (major rivers and catchments) where expropriation and development can be prioritised over biodiversity and *vice versa* (Rheinheimer *et al*. 2007). One approach proposed by Moyle (1996) is the concept of Aquatic Diversity Management Area, which is a formally identified catchment high in freshwater biodiversity, but placed within a larger resource management framework (Moyle and Yoshiyama 1994). A different approach is to focus on flow-regime prioritisation (e.g. native fish populations; Williams 2006*b*), wherein regulated catchments would have one of the following management priorities: (1) natural flow regime to maintain viable

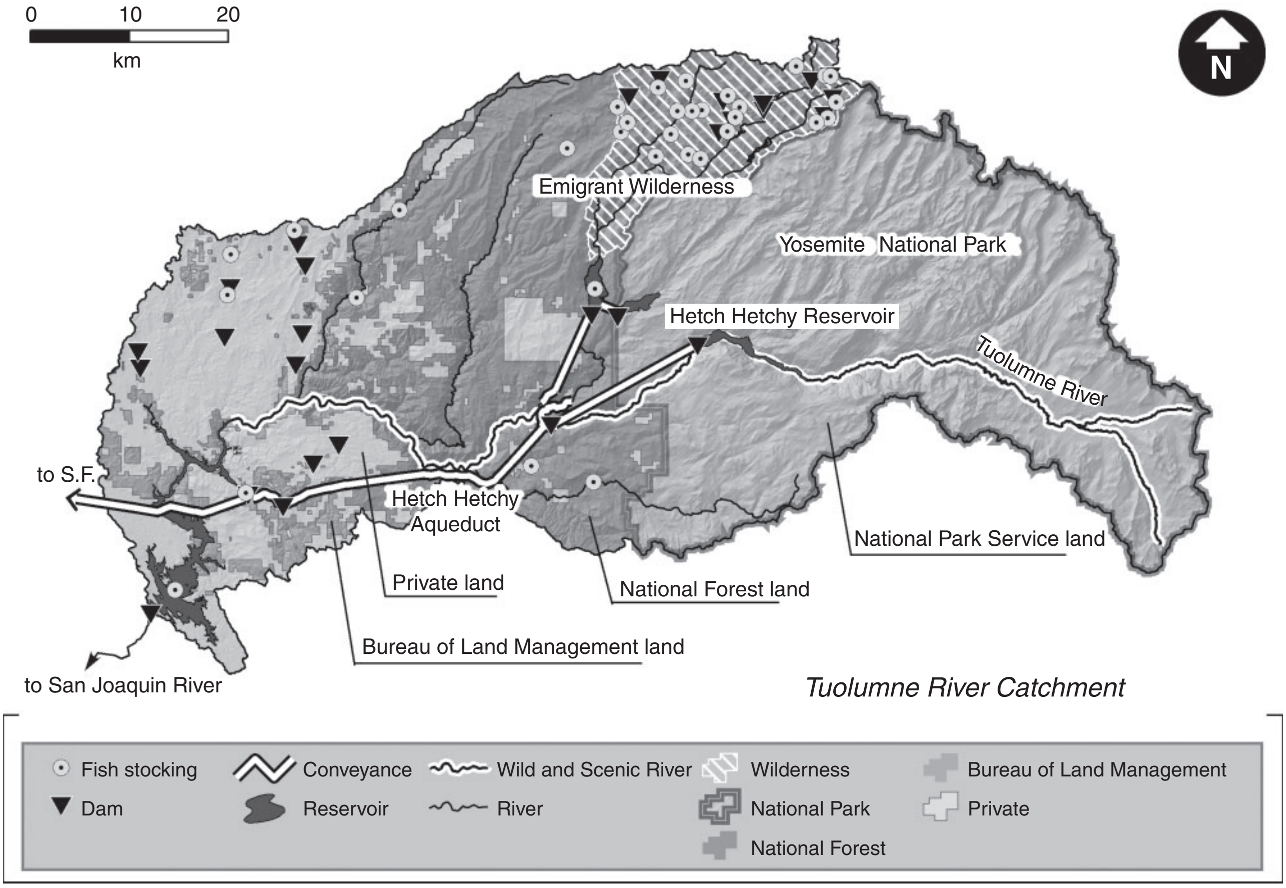

Fig. 2. Different land and water uses in the Tuolumne River catchment in the central Sierra Nevada: dams (hydroelectric), Hetch Hetchy aqueduct to San Francisco (S.F.) and fish-stocking areas that conflict with aquatic conservation targets.

populations; (2) adaptive and experimental management of in-stream flows to enhance recovery; and (3) status quo flow regulation, where population recovery is difficult and the other beneficial uses of water, such as hydropower and water supply, are highly desired. Such spatial optimisation of development of rivers (e.g. multiple dams on a single tributary as opposed to single dams on multiple tributaries) allows for a more coherent ecological and hydrological approach to conservation purposes (Richter *et al*. 2010).

Catchment specialisation, a type of triage, is an extreme prioritisation for multiple demands over large areas. This could produce improved freshwater biodiversity protection by systematically selecting for representation, viability and resilience; however, it would require regulatory and legal changes. The focus would be on high-priority catchments specialised for biodiversity and ecosystem value. In the Sierra Nevada, the Feather River could be managed for its water-delivery potential, the American River for its hydropower development and the Yuba River restored for anadromous salmonid recovery and persistence. There may also be niche environments with unique assemblages in developed rivers that must be aggressively managed for their ecological value (e.g. meadow complexes of Feather River headwaters). A regional vision is required, developed by all potential stakeholders and involving most, if not all, major basins and their downstream constituents, 38 million residents of California, well beyond the current IRWMP context.

Dam licensing and reoperation

For hydropower, there are potential operational improvements that would favour aquatic ecosystems (Rheinheimer *et al*. 2007; Viers 2011). This includes regionalisation of hydropower management, through coordination of mitigation and relicensing efforts, integration of adaptive management (Pahl-Wostl 2007; Pittock and Hartmann 2011) into operational requirements within FERC licenses and improved simulation and optimisation models for scenario analyses. There is also a need for parallel licensing, where there is explicit coordination of licensing dams within a large catchment, including coordination of inter-basin transfers. Currently, licencees can avoid consideration of cumulative or large-scale spatial effects, because they are considered outside the legal framework. Regional coordination would impose management for conservation, and optimise energy production for the power grid. The latter issue becomes even more critical with non-stationary hydrology, as is expected with climate warming, and managing water and power for uncertain futures (Pahl-Wostl 2007; Milly *et al*. 2008).

Also, aging of a dam or reassessment of its utility may warrant a decommissioning (Pittock 2010; Pittock and Hartmann 2011) or, at minimum, the construction of fish passage if required. Installation of outlet works to draw from different depths (Rheinheimer *et al*. 2007) would allow dam operators to release water optimally at desired temperatures to benefit downstream aquatic life avoiding unseasonal temperatures caused by thermal stratification. Other physical options include new pumped-storage facilities that pump water to hydropower-storage reservoirs during low demand to be released later when demand is high. Physical improvements or changes in dam operation can reduce the need for additional development (Richter *et al*. 2010), saving money and presumably improving environmental outcomes (Watts *et al*. 2010).

Integrating freshwater conservation principles

Effective conservation should also focus on emerging principles of systematic freshwater conservation planning (Nel *et al.* 2011). Freshwater systems require the following two key abiotic elements for biotic integrity: (1) connectivity, which provides panmictic reproductive opportunities for organisms, ensuring genetic diversity and evolutionary processes as habitats shift in space and time; and (2) flow regime, which underpins ecosystem and organisational responses. Development of water resources has severely altered the flow regime in most major river systems in the Sierra Nevada, fragmenting species assemblages, adapted to seasonal Mediterranean-montane hydrologic conditions. A freshwater conservation strategy should consider representation, persistence and quantitative targets (Nel *et al*. 2009). Representation ensures that all species, including rare and unique species, are considered; persistence ensures that targets remain viable over long time horizons (i.e. sustainable); and quantitative targets ensure that biodiversity conservation objectives are measurable and measured. Without a comprehensive biological inventory, meeting such criteria will remain difficult and so they must be a priority.

Strategic recommendations

For the western United States, including Sierra Nevada, the patchwork of regulatory and management mechanisms implemented by federal, state and local entities is ill-suited for sustaining freshwater biodiversity, and is generally problematic for water management under changing climatic conditions. The current patchwork approach to conservation inadequately addresses hydrologic connectivity against multiple inter- and intra-basin demands (e.g. Dunning and Galloway 2006). The *status quo* approach relies on reactionary 'sandbags and firehoses' as compensation for a lack of formal policy and will continue to be disastrous (de la Vega 2008). In the absence of a national policy to regulate and manage all facets of freshwater, we recommend a portfolio of strategies for catchments. Although specific in detail to Sierra Nevada, our recommendations are widely applicable.

Strategic portfolio

Anticipated hydrological alteration from climate warming will force some adaptation and change in behaviour. With its wide geographic scope and large societal magnitude, sustaining freshwater ecosystem services in the Sierra Nevada requires a diverse portfolio of legal, regulatory, managerial and economic strategies. A single, large formalised body responsible for directing water resource management and conservation priorities would simultaneously satisfy the competing demands on freshwater ecosystem services (Viers 2011). For example, a large federal authority manages the Columbia River system in the Pacific Northwest of the USA (Bonneville Power Administration), and a non-profit public-benefit corporation operates California's power grid (California Independent System Operator); each makes resource-allocation decisions to benefit a wide number of competing interests. More appropriate to the Sierra Nevada, the Tahoe Regional Planning Authority regulates, develops and coordinates resource management plans. The challenge of freshwater biodiversity conservation in the Sierra Nevada could be met with a series of similar regional agencies, each coordinating the development and integration of catchment-specific water-quality remediation measures, hydropower operating rules and habitat conservation plans to ensure public trust values (*sensu* Roux *et al*. 2008). By administering a portfolio of strategies, regional authorities can be more adaptive to changing resource conditions, anticipated with climate change, and ultimately more anticipatory in their decision-making.

Services strategy

Catchments of the Sierra Nevada provide nearly one-third of California's water supply and 20% of the state's renewable-energy supply via hydropower generation; thus, there is a strong incentive to retain the *status quo* for managing these ecosystem services. One mechanism to change resource management behaviours is to explicitly recognise the economic benefit downstream water users receive from upstream catchment stewardship and provide payments for ecosystem services (Chan *et al*. 2006). Antiquated notions of water rights and beneficial uses in the western United States have precluded any implementation of such payments, such as mitigation banking (i.e. a deeded land exchange for adverse environmental impacts incurred elsewhere) and environmental uses of water (Bricker and Filippi 2000). There is a move to embed payments for ecosystem services through the restoration of montane meadows of the Sierra Nevada, which are intended to dampen peaks of upstream hydrographs and elevate base flows, minimising downstream flooding and increasing dry-season water supply while also improving wildlife habitat (National Fish and Wildlife Foundation 2009). The National Fish and Wildlife Foundation will fund US$10 million to various organisations over 10 years to implement and monitor ecological and hydrological benefits of meadow restoration (National Fish and Wildlife Foundation 2009). Although this incentive may not prompt downstream stakeholders to pay for improved ecosystem services, it is a welcome development.

Management strategy

Protection of freshwater resources could be improved by providing mechanisms for volitional passage over barriers (e.g. fish ladders), and targeting management of regulated flows for ecosystems. Maintaining the natural features of the flow regime for endemic species is paramount to any successful management strategy intended to conserve freshwater biodiversity. Regulated river systems should be evaluated for the presence and condition of endemic-species assemblages or life-history traits that can be supported by regulated flows that mimic the natural flow regime or maintain downstream thermal regimes. Hydrologically connected rivers and streams with unimpaired flows should also be identified and prioritised for their resilience to hydrologic alteration from climate warming (Pittock and Finlayson 2011). When combined, this collection should form the basis for catchments prioritised for climate-warming resilience (see Pittock *et al*. 2008). Practical flow management should be adaptive (e.g. Watts *et al*. 2010), with formal hypotheses and actions as experiments, for established priority issues and areas, identified from a catchment assessment.

Collectively, the authorities and scientific expertise exist in Sierra Nevada for successful management. We recommend that federal land managers (e.g. USFS) drive this topic broadly, leveraging hydropower operators, licensed by FERC, to become integral partners in managing regulated river systems for biodiversity benefits. This management strategy will be strongest, coupled with a regulatory strategy, such as the suggested development of climate-warming alternatives in *NEPA*, and the development of a range wide HCPs under the *ESA* for freshwater biodiversity.

Regulatory strategy

Existing laws and regulations are well constructed and can be effective for conservation of freshwater biodiversity, even under changing climatic and hydrologic conditions, when implemented appropriately. However, few agencies have the requisite political mandate and funding necessary for meaningfully integrated decision-making. We recommend that agencies exercise their present authority, in anticipation of future effects of climate on flows. For example, federal resource management agencies protect species threatened with extinction under the *ESA*; yet, only recently has riverine habitat been designated above Sierra Nevada rim dams, deemed critical for the recovery of anadromous salmonid populations (National Marine Fisheries Service 2009). The development of basin-wide HCPs – previously developed only for terrestrial conservation purposes – could recover target species and manage ecosystems. It could also simultaneously encourage cooperation by minimising regulation and enforcing strict management of critical habitat (Bricker and Filippi 2000), with resilience to climate warming a designating factor. Rigorous environmental-impact assessments that include climate warming-induced hydrologic alteration as a *NEPA* alternative during FERC's licensure of non-federal hydropower generation under FERC could also be effective (Viers 2011).

At the state level, authorities enforce regulations. SWRCB should use its authority not only to regulate and enforce water-quality statutes (e.g. certification), but also to more rigorously investigate and enforce over- and mis-appropriations of water. California constitutional law requires that uses of water be beneficial to the public interest, and also be without waste. To this end, there has been little evidence of strict adherence or enforcement avoiding waste. Furthermore, the California Fish and Game Code specifies that dam operators must provide sufficient water to leave fish in 'good' condition (Moyle *et al*. 1998; Williams 2006*a*). If this provision were enforced for Sierra Nevada fish species and populations, it would also need other less codified laws (e.g. Public Trust Doctrine) to capture the full suite of regulated and unregulated fluvial habitats for ecosystem management.

Conclusions

The Mediterranean-montane climate of the Sierra Nevada is expected to warm by 2–6°C over the next century, reducing snowpack, causing early runoff and altering flows. This will present a grand challenge for the long-term conservation of freshwater ecosystems, which have experienced widespread extirpations of anadromous fishes, losses in amphibian abundance and increases in non-native species. Sustaining freshwater ecosystem services, and associated biodiversity, will require integration of regulatory, economic and conservation strategies, currently dispersed across a patchwork of laws, regulations and agencies, with no clear demarcation of roles and responsibilities. Weak implementation and lack of coordination among authorities has resulted in a reactionary, crisis-driven water resource management, poorly suited to adaptation.

To improve biodiversity condition and ecosystem services regionally, we recommend the following: (1) existing legal and regulatory authorities to be implemented to the fullest extent, and to incorporate future resource conditions into management; (2) local institutions to develop and implement a systematic freshwater conservation plan, with a focus on aquatic ecosystems resilient to hydrologic alteration from climate warming; (3) specialisation of catchments to emphasise disparate priorities, such as anadromous salmon populations or hydropower generation; and (4) catchment planning agencies with regulatory authority level to balance competing resource. Such recommendations are necessary not only to conserve freshwater biodiversity in Mediterranean-montane regions globally, but also to sustain human uses of water in a rapidly changing environment.

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