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Climatic influences and anthropogenic stressors: an integrated framework for streamflow management in Mediterranean-climate California, U.S.A.

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SUMMARY

1. In Mediterranean and other water-stressed climates, water management is critical to the conservation of freshwater ecosystems. To secure and maintain water allocations for the environment, integrated water management approaches are needed that consider ecosystem flow requirements, patterns of human water demands and the temporal and spatial dynamics of water availability.
2. Human settlements in Mediterranean climates have constructed water storage and conveyance projects at a scale and level of complexity far exceeding those in other, less seasonal climates. As a result, multiple ecological stressors associated with natural periods of flooding and drying are compounded by anthropogenic impacts resulting from water infrastructure development.
3. Despite substantial investments in freshwater ecosystem conservation, particularly in California, U.S.A., success has been limited because the scales at which river management and restoration are implemented are often discordant with the temporal and spatial scales at which ecosystem processes operate. Often, there is also strong social and political resistance to restricting water allocation to existing consumptive uses for environmental protection purposes. Furthermore, institutions rarely have the capacity to develop and implement integrated management programmes needed for freshwater ecosystem conservation.
4. We propose an integrated framework for streamflow management that explicitly considers the temporal and spatial dynamics of water supply and needs of both human and natural systems. This approach makes it possible to assess the effects of alternative management strategies to human water security and ecosystem conditions and facilitates integrated decision-making by water management institutions.
5. We illustrate the framework by applying a GIS-based hydrologic model in a Mediterranean-climate watershed in Sonoma County, California, U.S.A. The model is designed to assess the hydrologic impacts of multiple water users distributed throughout a stream network. We analyse the effects of vineyard water management on environmental flows to (i) evaluate streamflow impacts from small storage ponds designed to meet human water demands and reduce summer diversions, (ii) prioritise the placement of storage ponds to meet human water needs while optimising environmental flow benefits and (iii) examine the environmental and social consequences of flow management policies designed to regulate the timing of diversions to protect ecosystem functions.
6. *Thematic implications*: spatially explicit models that represent anthropogenic stressors (e.g. water diversions) and environmental flow needs are required to address persistent

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and growing threats to freshwater biodiversity. A coupled human–natural system approach to water management is particularly useful in Mediterranean climates, characterised by severe competition for water resources and high spatial and temporal variability in flow regimes. However, lessons learned from our analyses are applicable to other highly seasonal systems and those that are expected to have increased precipitation variability resulting from climate change.

Keywords: endangered species, environmental flow, hydrologic variability, salmonids, seasonality, water resource management

Introduction

Mediterranean-climate regions are concentrated centres of both human populations and agricultural production. Consequently, competition for water in these areas is among the highest in the world (Gasith & Resh, 1999). Human needs for fresh water in Mediterranean-climate areas are further complicated by unpredictable, annual water supplies and the seasonal disconnect between when water is available and when demand is highest. Unpredictable annual precipitation and limited water availability during the dry season have resulted in extensive water infrastructure development, which complicate efforts to restore and manage freshwater ecosystems. Thus, the global challenge of balancing ecosystem integrity with societal water needs (Baron *et al.*, 2002) is particularly acute in Mediterranean climates.

The conservation of freshwater ecosystems requires new water management approaches that consider both societal and ecosystem needs in an integrated fashion (Wallace, Acreman & Sullivan, 2003). Integrated water resources management is particularly needed in Mediterranean-climate regions, where the conservation of stream ecosystems requires the modification or curtailment of human water use practices. In these regions, and in other areas of the world with water-stressed systems, the maintenance of natural flows through environmental water allocations is essential to the conservation of freshwater ecosystems (Arthington *et al.*, 2006; Dudgeon *et al.*, 2006; King & Brown, 2006). Yet, substantial scientific, social and institutional challenges continue to hinder the implementation of ecologically sustainable water management.

In this article, we highlight the importance of integrated streamflow management in Mediterranean climates and describe a framework that takes into account the complex dynamics of water availability, human water demands and ecosystem needs at appropriate spatial and temporal scales. First, we describe patterns of water resources development in Mediterranean-climate regions and their associated ecosystem effects. Second, we discuss the challenges of river ecosystem management and environmental water allocations in these systems. Third, through an example from a Mediterranean-climate California watershed, we demonstrate how a coupled human–natural system approach to river management makes it possible to meet agricultural water demands while optimising environmental flow protections, as well as to evaluate the potential consequences of alternative water management policies. Finally, we highlight its applications for managing water resources for ecosystem and human needs in other seasonal climates.

Mediterranean-climate regions

Mediterranean-type climates occur on all continents, extending between 30 and 40° latitude both north and south of the equator. Most of this climate type is located around the Mediterranean Sea. On the Pacific coast of North America, the Mediterranean-climate region extends from southern Oregon to northern Baja California. Other parts of the world with a Mediterranean climate include parts of west and south Australia, the south-western Cape region of South Africa, and the central Chilean coast (Ashmann, 1973).

Mediterranean climates, which are often westerly positioned, are the result of a symmetrical atmospheric circulation that produces a characteristic pattern of cool, wet winters and dry, hot summers (Ashmann, 1973). Moderating oceanic influences keep winter temperatures mild, with mean monthly temperature minima between 8 and 12 °C; summer maxima typically range from 18 to 30 °C (Gasith & Resh, 1999).

Mediterranean-climate regions exhibit predictable, seasonal patterns of rainfall and drought. Most of the annual precipitation is concentrated over a few months in the winter, and there is often little to no rain from late spring to early fall. Compared to other regions with similar total annual rainfall, the amount and timing of precipitation within the wet season is also highly variable between years, leading to an extremely uncertain renewable supply of fresh water (Merenlender, Deitch & Feirer, 2008). In addition to high temporal variability in precipitation, Mediterranean systems often have complex tectonic and geologic conditions that result in high levels of spatial heterogeneity in streamflow regimes within river basins (Conacher & Sala, 1998).

Water resources development in Mediterranean climates

Mediterranean regions are highly suitable for human habitation and have settlements that can be traced back to the earliest civilisations. It is not surprising that humans found these areas attractive given the rich soils, abundant sun and long growing season. Today, Mediterranean-climate regions continue to support concentrated human populations and are global centres of agricultural production.

In Mediterranean-climate regions, freshwater lakes are rare and ground water is often restricted to river flood plains, so human settlements rely extensively on streams and rivers to meet their water demands for agriculture, industry and domestic consumption (Gasith & Resh, 1999). The withdrawal of water for agricultural irrigation in these regions typically represents the vast majority of total human water use (e.g. up to 80%), although water withdrawals for urban use has been increasing in Mediterranean-climate regions with growing populations such as California (Konieczki & Heilman, 2004) and in countries such as Spain, Morocco and Israel [World Commission on Dams (WCD), 2000].

Most of the human water demands in Mediterranean-climate areas occur in the dry summer months, when water is required for agricultural irrigation yet precipitation is rare. Thus, the asynchronous timing of water availability and demands, together with high interannual variability of Mediterranean river flows, have lead to the development of large-scale water storage and irrigation projects to maintain reliable water supply. In fact, the extensive manipulation of rivers to provide reliable access to water is a defining characteristic of Mediterranean systems (Kondolf & Batalla, 2005). In California, for example, every major stream has been affected by the construction of dams and reservoirs to increase water supply security for agricultural and urban water users (Moyle, 2002).

While water infrastructure development has increased water security for human settlements, it has also substantially altered the natural flow dynamics of river and streams. The hydrologic alterations to rivers associated with large water projects are well documented in Mediterranean climates and throughout the world. Large dams are specifically intended to alter the natural distribution and timing of streamflow (Poff *et al.*, 1997), and disruption to natural flow regimes occurs both upstream and downstream of dams and major diversions (e.g. Graf, 1999; Cowell & Stoudt, 2002; Nilsson *et al.*, 2005; Richter & Thomas, 2007). Water infrastructure development also often entails the transfer of water across natural geographical boundaries. These interbasin transfers augment water supplies in some basins while dewatering the basin of origin, altering natural flow patterns across broad geographical regions (Davies, Thoms & Meador, 1992).

In areas not served by large reservoirs, small water projects are common, including surface water diversions and ground water pumping. Direct withdrawal of water from streams can result in decreased flows by more than 90% locally and can produce significant cumulative downstream effects (Deitch, Kondolf & Merenlender, 2009a). As alternative to on-demand withdrawals from streams or ground water, small water storage basins (also referred to as farm ponds) are often built that are filled from surface water diversions and run-off captured in the winter for later use in the growing season. The hydrologic impacts of small storage ponds are less well studied than large reservoirs, although they are likely to have similar effects on downstream flows albeit on a smaller scale.

Biological responses to Mediterranean climates

In Mediterranean climates, seasonal fluctuations in streamflow, as well as episodic disturbance events (e.g. interannual floods and drought), have a dominant influence on freshwater ecosystem structure and function (Resh *et al.*, 1988). Mediterranean stream biota experience the sequential occurrence of extreme abiotic disturbance (e.g. winter floods), followed by a period of increased biotic interactions (e.g. predation and competition for food) as lotic habitats become more lentic, and finally more abiotic pressures as drying and loss of hydrologic connectivity occurs (Gasith & Resh, 1999; Bonada *et al.*, 2006).

The influence of climate variability on ecosystem structure and functions has been studied across all trophic levels in diverse Mediterranean-stream systems. Most studies of climatic influences on biota have focused on macroinvertebrates, demonstrating strong effects of seasonal and interannual precipitation patterns on the composition and abundance of benthic species (e.g. Bêche, McElravy & Resh, 2006; Bonada *et al.*, 2006; Elron, Gasith & Goren, 2006; Bêche & Resh, 2007; Bonada, Rieradevall & Prat, 2007; Daufresne, Bady & Fruget, 2007; Dewson, James & Death, 2007; Rader, Voelz & Ward, 2008). Hydrologic variability has also been demonstrated to have strong effects on fish assemblages (e.g. Bernardo *et al.*, 2003; Magalhães *et al.*, 2007; Bêche *et al.*, 2009), primary productivity (e.g. Marks, Power & Parker, 2000; Schemel *et al.*, 2004) and food web structure (e.g. Power, Parker & Dietrich, 2008; Strayer *et al.*, 2008).

In Mediterranean climates, native biota have developed a variety of mechanisms to tolerate the environmental stressors of seasonal flooding and drying and associated changes in habitat conditions (Fox & Fox, 1986). For example, Bonada, Dolédec & Statzner (2007a) found that, in comparison with temperate-climate streams, macroinvertebrates from Mediterranean streams tended to have life history traits that provided greater resistance to droughts and improved ability to recovery from disturbance. Mediterranean-stream fish species also have life history traits that enhance their ability to cope with hydrologic variability, including short lifespans, rapid growth rates and high fecundity (Ferreira *et al.*, 2007), as well as behavioural adaptations to respond to flow-related stressors, such as migratory movement to refugia during drought periods (Magoulick & Kobza, 2003).

There is also evidence that natural hydrologic disturbance plays an important role in structuring species assemblages in Mediterranean streams. For example, Marchetti & Moyle (2001) demonstrated that native fishes in a regulated California stream responded positively during wet years when flow conditions were more similar to their natural regime. In drier years, when dam releases are reduced in the summer, lower flows and higher temperatures created habitat conditions that were less suitable for native fish species and more favourable for non-native fishes. Episodic, bed-souring winter flows have also been shown to be important for structuring river ecosystems, influencing algal biomass, invertebrate communities and trophic interactions that persist through the low-flow season (Power *et al.*, 2008).

Despite the importance of natural hydrologic disturbance in mediating biotic interactions and community structure, Mediterraenan freshwater ecosystems are highly susceptible to impacts from water management operations and other anthropogenic disturbances (Alvarez-Cobelas, Rojo & Angeler, 2005). Not only does water infrastructure development tend to be extensive in Mediterranean-climate regions (Kondolf & Batalla, 2005), but the highly adapted nature of native aquatic species to natural flow variability (Lytle & Poff, 2004) may make them particularly vulnerable to activities that affect natural flow patterns. Storage reservoirs and dam operations tend to reduce flow variability (Poff *et al.*, 2007) and, particularly in the dry season, diversions can reduce flows that are necessary to maintain stream habitat conditions. The vulnerability of freshwater species to flow regime impacts combined with the pervasive extent of water resources development in Mediterranean-climate regions, thus makes water management a key issue for freshwater ecosystem conservation (Richter *et al.*, 2003; Dudgeon *et al.*, 2006).

Water management operations, such as diversions, dams and flow regulations, interfere with fundamental hydrologic processes that control habitat structure, the intensity and frequency of scouring floods, floodplain interactions and water quality conditions (Bunn & Arthington, 2002). Water management activities commonly associated with ecosystem impacts can be grouped into four broad categories: (i) water diversions, (ii) impoundments, (iii) dam operations and (iv) interbasin transfers. The ecological effects of these activities on freshwater ecosystems are well documented (reviewed by Poff *et al.*, 1997; Bunn & Arthington, 2002; Murchie *et al.*, 2008; Haxton & Findlay, 2008; summarised in Table 1).

Although less well studied than dams and diversions on large rivers, water management of small, unregulated streams can also impair ecologically relevant flow regime characteristics. In stream

Table 1 Summary of hydrologic and ecological impacts of water management operations

Water Management Activity	Hydrologic alteration	Ecological impact
Water Diversions	Reduction in baseflow magnitude and increase in duration	Reduced dilution capacity and water quality conditions favourable to pollution-tolerant species (2), concentration of aquatic organisms and increased biotic interactions (5), reduction or elimination of plant cover (5), loss of riparian species diversity (5)
	Acceleration of streamflow recession/drying	Failure of riparian seeding establishment (5), change in macroinvertebrate composition (2), decreased macroinvertebrate abundance (3)
	Lowered water table	Loss of riparian vegetation (2, 5)
	Siphoning of surface waters	Aquatic species mortality from entrainment (1)
Impoundments	Reduction in frequency, duration and area of flooding	Reduction in inundation period of floodplain habitats used by fish for spawning and foraging (1, 5), decline in waterfowl species richness and abundance (1), shifts in riparian community composition (1), ineffective seed dispersal (5), encroachment of riparian vegetation and simplification of river channel habitats (5)
	Reduction in sediment load and resulting downstream channel incision and bed armouring	Reduction in habitat complexity and species richness (5)
	Reduction in longitudinal connectivity	Barrier to migratory fish (1)
	Conversion of lentic to lotic waters	Elimination of salmonids and native pelagic spawning fishes (1), loss of fish populations from inundation of spawning habitats (1), establishment of exotic species (1, 5)
Dam operations	Reduction in flow variability	Increase in exotic fish species (1, 4), reduced abundance of fluvial specialists (3)
	Increase in low/baseflows magnitude and duration	Reduction in fish populations (1), proliferation of nuisance species (1), physiological stress to riparian vegetation and diminished plant species diversity (5)
	Increased rates of water level fluctuation and erratic flow patterns	Reduction of richness and standing crop of benthic macroinvertebrates (1), washout or stranding of aquatic species (5), decreased macrophyte growth rates and seedling survival (5)
	Loss or shift in timing of seasonal flow peaks	Excessive growth of macrophytes (1), reduction of riparian tree seedling recruitment (2, 5), life cycle disruption (1, 5), loss of cues for fish migrations and impairment of fish spawning and egg hatching (1, 4, 5), modification to food web structure (5)
	Modified temperature regimes downstream	Delayed spawning in fish (1), disrupted insect emergence patterns (1), elimination of temperature-limited species of fish (1), reduced abundance of aquatic fish and macroinvertebrate communities (3)
Interbasin Water Transfers	Increased hydrologic connectivity across natural geographical barriers	Spread of disease vectors (1), translocation of aquatic species outside of natural range (1)

References are limited to reviews and meta-studies, in which specific examples of ecological responses to flow regime alterations from water management activities are documented. Sources: (1) Bunn & Arthington, 2002; (2) Gasith & Resh, 1999; (3) Haxton & Findlay, 2008; (4) Murchie *et al.*, 2008; and (5) Poff *et al.*, 1997.

catchments where water demand is high, the local and cumulative impacts of surface water diversions have the potential to accelerate drying over extended stream reaches and to reduce habitat availability for aquatic species (McKay & King, 2006; Spina, McGoogan & Gaffney, 2006; Deitch *et al.*, 2009a). The ecological responses to decreased low flows remain poorly understood, but artificially reduced flows from water extractions are likely to result in shifts in the abundance, diversity and composition of both invertebrate and fish species (Dewson *et al*., 2007).

In Mediterranean and other climatically variable systems, flow regime alterations from water management operations have played a dominant role in the decline in freshwater biodiversity (Dudgeon *et al*., 2006). In California, water diversions have been identified as the most significant human activity negatively affecting fish diversity, where 40% of native fish populations have been driven to extinction or are in serious decline (Moyle, 2002). Similar patterns of freshwater ecosystem degradation are observed in Mediterranean Europe, where water development has contributed to a 50–100% decline of native fish species abundance since the beginning of the 20th century (Aparicio *et al*., 2000).

Freshwater conservation and streamflow management

Freshwater ecosystems have experienced widespread degradation at a global scale and generally remain poorly protected despite persistent and growing threats (Dudgeon *et al*., 2006). In Mediterranean-climate regions such as California, conservation and restoration programmes have failed to reverse the trend of freshwater biodiversity loss or achieve substantive protections of environmental flows for endangered aquatic species, despite investments of more than 2 billion dollars ($US) to date on restoration projects alone (Kondolf *et al*., 2007).

In our view, the limited success of freshwater ecosystem conservation in California, as well as in other Mediterranean-climate regions, is largely attributed to three important factors. First, the temporal and spatial scales at which conservation and restoration programmes are conducted are often discordant with the scales at which ecosystem processes operate. Second, there is strong social and political resistance to restrict water allocations to existing consumptive uses for environmental flow protection purposes. Finally, institutions do not have the capacity to develop and implement integrated programmes required for sustainable freshwater management.

Problems of scale

The effectiveness of freshwater conservation has been compromised by the limited extent at which conservation programmes and restoration treatments are actually implemented. In Mediterranean and other climate types, restoration has traditionally been conducted at the reach scale and been focused on the recovery of form and pattern, and thus produced limited ecological benefit when fundamental ecosystem processes (e.g. watershed hydrologic functions) have been altered (Wohl *et al*., 2005; Kondolf *et al*., 2006). The fragmented approach to restoration is highlighted in a recent assessment of river restoration projects in California by Kondolf *et al.* (2007), who found that of the projects surveyed, <10% considered a broader watershed management plan during site selection and project design. They conclude that most restoration projects fell short of restoring dynamic watershed processes and thus probably are of limited ecological value.

In contrast to the predominant approach to restoration described earlier, many restoration scientists have now come to understand that the restoration of an acceptable range of variability of process is more likely to succeed than restoration aimed at a static state that neglects environmental variability (Richter, 1997; Wohl *et al*., 2005). This latter approach requires increasing the spatial scales at which restoration programmes are commonly planned and implemented.

Finally, the conservation of Mediterranean freshwater ecosystems not only requires consideration of spatial scale, but also must address the challenges associated with the temporal variability of precipitation and streamflow patterns. Because Mediterranean systems are characterised by long-term disturbance regimes, episodic and extreme flood events in Mediterranean rivers can significantly alter river morphology and vegetation patterns. Depending on the elapsed time since the last major flood, Mediterranean rivers may exhibit strikingly different characteristics in morphology, vegetation patterns and biological community composition (Hughes, Colston & Mountford, 2005). Because our knowledge of the range of natural river states is often limited, it is difficult to establish meaningful baseline conditions to set restoration objectives (Wohl *et al*., 2005). Furthermore, natural climatic variation causes fluctuations in the abundance and distribution of species of concern, which obscures larger-scale trends and human-related factors responsible for population declines (Ferreira *et al.*, 2007).

Challenge of balancing human and natural system water needs

The effectiveness of freshwater ecosystem conservation has also been limited in Mediterranean climates because of the high competition for water resources. Conservation of freshwater biodiversity often requires making trade-offs between environmental and human water uses (Baron *et al.*, 2002; Poff *et al.*, 2003; King & Brown, 2006). To protect water allocations to stream ecosystems, minimum flow thresholds are often imposed to restrict human consumptive uses. Such measures are often critical for maintaining natural flows in streams, yet often stimulate significant social, political and economic friction. As a result, environmental water allocations to improve ecological conditions are rarely considered in river restoration practice, which remains mostly focused on habitat improvements such as planting riparian vegetation, reducing sediment and reconstructing stream channels (Christian-Smith & Merenlender, 2008). Our experience from California suggests that when conservation efforts do address environmental flows, a strong connection with endangered species populations must be established. Although changes in dam operations are increasingly considered for the recovery of aquatic ecosystems (Richter & Thomas, 2007), environmental flow protections remain weak or nonexistent in the vast majority of rivers and streams affected by diversions and dams. Furthermore, the integration of environmental flow allocations in water management has largely been focused on regulated rivers, while strategies for protecting environmental flows in smaller, unregulated streams that are affected by water diversions have received far less attention.

Human population growth and climate change are expected to impose increasing pressures on freshwater resources, placing even greater constraints on aquatic species conservation (Postel, Daily & Ehrlich, 1996). In the Mediterranean basin, for example, most of the available water resources have already been developed, while population growth and urbanisation are expected to significantly increase human water demands (Araus, 2004). In addition, global climate change is likely to lead to increased temperatures and changes in the amount and timing of rainfall (Mannion, 1995), further reducing regional human water security. In Mediterranean systems, as well in other water-stressed regions, balancing human and ecological water needs remains a daunting challenge for freshwater ecosystem conservation.

Institutional constraints

Governmental institutions responsible for freshwater ecosystem protections and allocations of water resources are often poorly equipped to implement the types of integrated approaches required for sustainable water management. For example, increasingly larger scales of water infrastructure development in Mediterranean regions has been coupled with increasing scales of governance over these systems, which often lead to distinct regional, national and international administrative systems of management control. The increasing scales of water management institutions have enabled the construction and operation of large-scale water projects that have allowed for economic growth in areas that otherwise would be constrained by water scarcity. However, the development of large-scale institutions has also led to the fragmentation of water management authority. In California, for example, distinct authorities are responsible for regulating water quality (to protect beneficial human uses), managing historic water rights (to protect economic interests of individual water users) and, more recently, ensuring aquatic species protections. There is also a division of control among institutions depending on the origin of fresh water being used. For example, in Calfornia, the State Water Resources Control Board (SWRCB) regulates surface water diversions but has no authority over ground water use, despite the fact that, in many cases, regional surface water and ground water sources are hydrologically connected (Sax, 2003).

When responsibility for social, economic and environmental protections are partitioned in this way, an action of one institution consistent with its legal mandate can have unanticipated effects on the others. For example, legal stream withdrawals by private landowners may cumulatively impact the amount and timing of water delivery to city or regional water authority and/or environmental flows necessary to support endangered aquatic species. In other contexts, flow releases from dams to meet environmental flow regime targets can reduce water security for farmers or affect trans-boundary water agreements. Inevitably, the multiple and often overlapping scales of jurisdiction, coupled with the fragmentation of governance structures, impede institutions from performing the fundamental tasks of integrated water management. Consequently, broad-scale assessments of water availability and uses, coordinated monitoring and decision-making, planning and implementation are often suboptimal (Davis, 2007).

Integrated framework for streamflow management: examples from the Russian River Basin, California, U.S.A.

In the light of the problems facing freshwater conservation in Mediterranean-climate regions, we propose an integrated framework for streamflow management that explicitly considers the temporal and spatial dynamics of water supply and the needs of both human and natural systems and that is intended to facilitate analysis and decision-making at broad geographical (e.g. basin) scales. This framework relies on a GIS-based hydrologic model to: (i) quantify patterns of water availability at scales relevant to ecosystem needs, (ii) represent the timing, magnitude and location of human water demands in relation to ecosystem flow requirements and (iii) calculate the local and cumulative impacts of alternative water management strategies. Our modelling framework addresses river ecosystems that are characterised by high variability in flow conditions and subject to population and land-use pressures that require year-round water supplies. This model is particularly well suited to assess decentralised water management systems, such as free-flowing rivers and streams that are affected by a spatially distributed network of water users. Through an example from a northern California watershed, we demonstrate that despite the complexity and pressures on streams in Mediterranean climates, it is possible to reduce potential ecosystem impacts while addressing human water needs.

Study area

The Russian River basin is a large coastal watershed (3900 km^2) in northern California, where 11 incorporated cities ranging from the densely populated Santa Rosa in the south (population 150 000 in 2000) to more rural communities in the north. The basin is also one of California's premium wine-grape growing regions and supports a thriving tourist economy. As in other Mediterranean climates, many smaller and upland watersheds are increasingly being used to grow high-value agricultural crops, such as vineyards, olive trees and avocados (Merenlender, 2000). Two large reservoirs in the basin supply most of the urban water demand in the region, while vineyards and other agriculture rely almost entirely on locally available surface and ground water resources.

The Russian River basin is home to three salmonid species listed under the federal Endangered Species Act: the central California coast Coho salmon (*Oncorhynchus kisutch*), central California coast steelhead trout (*Oncoryhnchus mykiss*) and California coast Chinook salmon (*Oncorhynchus tshawytscha*). Although several factors have contributed to population declines, flow regime and water quality alterations resulting from water management are considered a primary threat to California's salmonid species (Moyle, 2002).

California salmonids are highly adapted to the natural flow regime of coastal rivers and streams. Lower-velocity, winter baseflows between storm events allow adult salmonids to migrate from the ocean to spawning grounds and provide suitable hydrologic conditions for egg incubation. Winter peak flows are important for maintaining appropriate sediment distributions for spawning and preventing vegetation encroachment into the stream channel. In the spring, streamflows maintain hydrologic connectivity, allowing for juvenile out-migration and providing food resources via downstream drift. Summer flows maintain connectivity until streams approach or become intermittent, whereby pools continue to provide over-summering habitat until flows resume again in the fall (Kocher, Thompson & Harris, 2008). These lower spring and summer flows are critical for maintaining suitable habitat for juvenile rearing, and may be particularly vulnerable to impacts from diversions because water demands are greatest during the dry season.

An increase in catchment storage capacity through small distributed storage ponds (with average volumetric capacities of 50 000 m^3) provides one alternative to pumping water on demand from rivers or ground water during the dry season. Where local water demands are met by direct surface water diversions, the ability to irrigate from stored winter water has the potential to ameliorate the impacts on summer environmental flows. However, consideration must also be given to potential impacts on winter flows, because storage ponds are expected to reduce downstream flows until they are filled. Yet little is known about the extent to which distributed networks of small water storage projects lead to individual and cumulative impacts on environmental flows (Merenlender *et al.*, 2008). Most studies on trade-offs between water storage benefits and environmental flows have focused on large dam operations (e.g. Richter & Thomas, 2007) and not on decentralised water management.

The volumes of water required for vineyard irrigation typically represent a small fraction of the total water availability in the winter months (Deitch, Kondolf & Merenlender, 2009b). Therefore, the specific challenge in this system is to determine the number, size and locations of winter storage ponds needed to offset summer water demands without significantly impacting winter environmental flows. Our model is designed to examine the effects of alternative water storage scenarios and makes it possible to prioritise sites where storage will provide the greatest benefit to summer environmental flows while considering potential winter flow impacts.

Another important application of our model is to assess the effects of alternative water policies on the timing and magnitude of allocations to meet human and ecosystem needs. Where environmental flow protections are needed to conserve freshwater ecosystems, the model provides a tool to understand the consequences of flow protections on both ecological and human systems across spatial and temporal scales.

Methods

We use a GIS-based (ArcGIS version 9.2; ESRI, 2006) hydrologic model developed by Merenlender *et al.* (2008) to examine the effects of small water storage ponds on streamflow regimes throughout the year, in a 16 km^2 catchment in Sonoma County, California. The model estimates stream discharge (m^3 s^{-1}) at all points in a drainage network based on records from a nearby USGS gage station (Maacama Creek #11463900, in eastern Sonoma County, CA, U.S.A.), scaled according to watershed area and annual precipitation differences. For this exercise, we used flow data from a normal rainfall year (e.g. 1966, a year with median annual discharge), although any hydrograph may be specified in the model.

We digitally mapped hypothetical storage ponds on the landscape, specifying their coordinate locations and volumes. The model was then run to route flows through the catchment with specifically placed storage ponds, which are assumed to capture all upstream run-off until they are filled. For each scenario, the model calculates the flow impact (e.g. percentage of flow removed from stream compared to unimpaired flow) below each reservoir. These effects are then propagated down the stream network.

The downstream impact of a pond depends on its volume and location in the drainage network, and pond effects can be described by the degree of flow impairment (e.g. percentage of natural flow removed from channel downstream), impact length (e.g. length of channel downstream that flows remain impaired) and duration of impairment (e.g. number of days in which flows are impaired as the pond fills). To compare the impacts of different water storage sites, we developed an impact index that aggregates each of these pond impact types, based on the following metric:

$$\begin{aligned}\text{Impact Index} = {} & \text{Number of impact days} \\ & \times \sum_{1}^{n}(\text{Segment length} \\ & \times \text{Percentage of flow impairment}), \\ & \text{for } n \text{ flow-impaired,} \\ & \text{10-metre stream segments} \\ & \text{below storage pond location.}\end{aligned}$$

This impact index is useful because it captures both the spatial and temporal extent of downstream effects on winter flows.

To consider the environmental and human-system effects of surface water storage within the study catchment, we applied the model in three ways. First, we placed three hypothetical storage ponds of equal volume in the catchment and calculated their individual and cumulative downstream impact indices. This application of the model demonstrates how the impacts of storage ponds are influenced by upstream area and downstream drainage network configuration. The example also serves to illustrate how multiple ponds interact to produce cumulative effects on streamflow.

In the second example, we placed hypothetical ponds on landholdings with existing vineyards, setting the storage volume of each pond equal to the estimated annual water demand of that vineyard (e.g. *c.* 0.2 m^3 m^{-2}). We then calculated the impact index of each reservoir and compared them to the benefits they provide in offsetting summer water demands in the catchment. Based on this benefit-to-impact ratio, we ranked each of the hypothetical ponds, illustrating how the strategic prioritisation of storage projects could be achieved.

In the final example, we examined the potential consequences of a proposed California streamflow management policy on both winter and summer environmental flows [State Water Resources Control Board (SWRCB), 2007]. The policy is designed to protect winter environmental flows and restricts water diversions to periods when flow exceeds a threshold level necessary for upstream salmon migration. The flow threshold is defined as the minimum flow necessary for maintaining sufficient water depths for adult salmon passage. We ran the model for each of the ponds from the previous example, under the policy scenario where the timing and volume of diversions are restricted to protect winter environmental flows. We then assessed how implementation of the policy would modify winter flow impacts, storage volumes of winter water and potential demands on summer flows.

Example 1: effects of storage pond location on streamflow

As discussed previously, one solution to offset summer flow impacts is to capture water from winter flows into storage ponds for use during the irrigation season. However, the placement of ponds within a catchment requires consideration of impacts on winter environmental flows, which are important for fish migration and channel maintenance. The impacts of three hypothetical ponds placed in the study watershed are illustrated in Fig. 1. All three of the ponds have the same storage capacity but have substantially different impacts on downstream flows because of

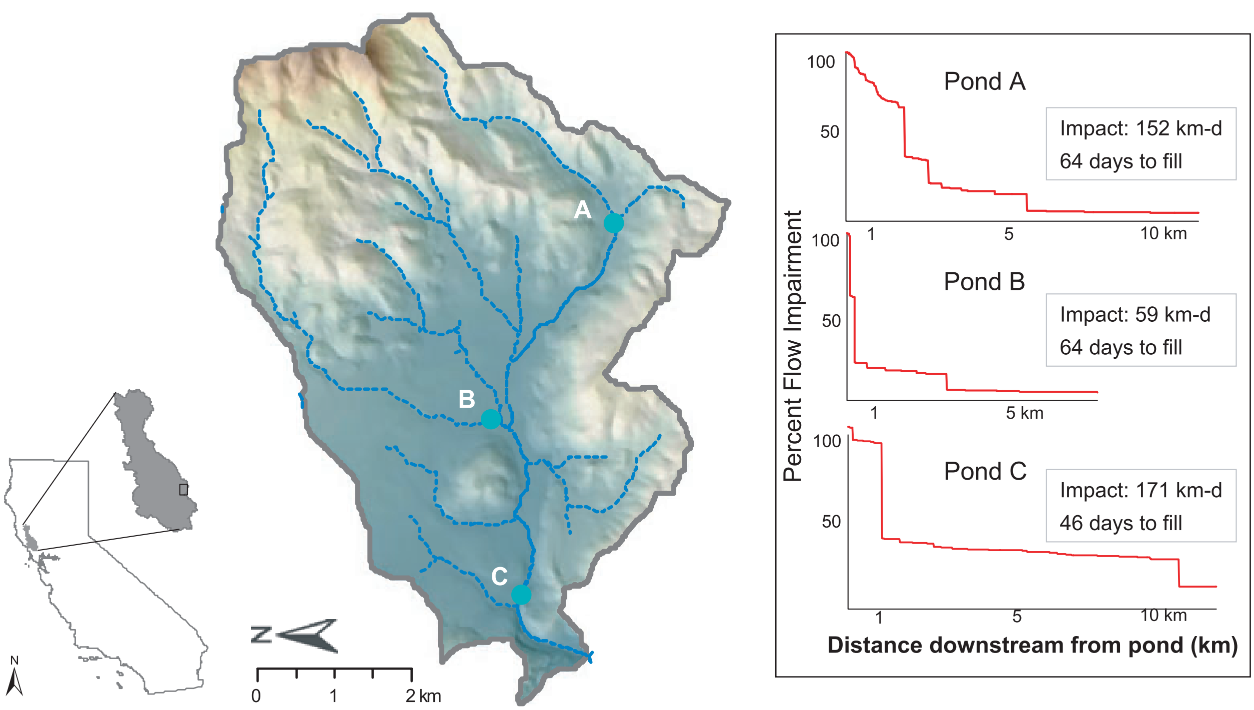

Fig. 1 Location of three hypothetical agricultural storage ponds (blue circles) of equal volume placed in a subcatchment of the Russian River in northern California, U.S.A. Graphs in right panel show the impact of each pond as percentage of flow impaired with increasing downstream distance from the pond location and report the impact index and time to fill.

differences in site location and upstream drainage area.

The model results show that Pond A has a greater downstream impact on winter flows than Pond B (Fig. 1). Because Ponds A and B have the same catchment area (3 km^2), the number of days to fill is the same (64 days), after which spillover occurs and flows are unimpaired. However, flows from the tributary downstream of Pond B reduce the impact of the reservoir compared to Pond A. Therefore, the impact index of Pond A (152 km day) is nearly three times as great as that of Pond B (59 km day).

The impact index of Pond C (171 km day) is greater than those of both A and B. Pond C has the same volume as Ponds A and B, but fills more rapidly (46 days) because of the greater upstream drainage area. However, Pond C has a much larger downstream effect than Ponds A and B because it captures run-off from a larger drainage area, cutting off significant flow contributions to the channel downstream.

The model indicates that early-winter streamflow at the catchment outlet is impaired by as much as 90% when the cumulative effects of all three ponds are analysed. The impact index of all three ponds together is 446 km day, which is substantially larger than the sum of the impacts of the three ponds considered separately (*c.* 382 km day), illustrating the potential for multiple ponds to interact and produce significant cumulative effects on streamflow.

Example 2: targeting sites for storage by optimising environmental flow benefits

Strategic placement of storage ponds across the landscape could theoretically reduce or eliminate summer water withdrawals, protecting environmental flows in the dry season. However, as illustrated in Example 1, ponds have the potential to impact winter environmental flows. Therefore, the allocation of storage throughout a basin should consider the trade-offs associated with the benefits and impacts of specific pond locations.

When we run the model to evaluate the effects of 14 hypothetical storage ponds, sized to meet the water demands of the surrounding vineyard parcel, we again find that individual impacts vary depending on their storage capacity, upstream drainage area and location in the stream network (Fig. 2; Table 2). The 14 ponds range in volume from 10 000 to 150 000 m^3 and

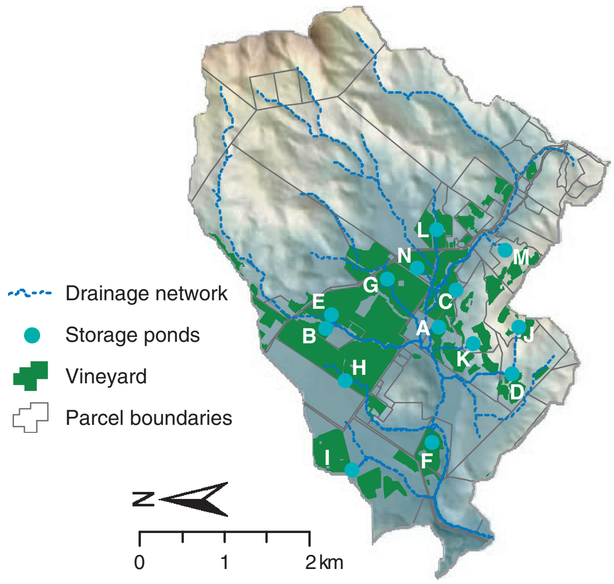

Fig. 2 Locations of hypothetical storage ponds (blue dots) required meet vineyard water demands on privately owned parcels within the study catchment.

have upstream drainage areas of 0.04–1.2 km^2. The impact indices range substantially, from approximately 6 km day (Pond B) up to 105 km day (Pond H).

When the individual ponds are ranked based on their benefit-to-cost (% of catchment storage-to-impact index) ratio (Table 2) and plotted against the proportion of water demand for the catchment, we see that approximately 70% of basin water demand could be offset by locating ponds at 6 of the 14 sites (Fig. 3). The marginal increase in storage gained by adding more ponds decreases after the sixth highest-ranking site.

Example 3: consequences of environmental flow policies

As the final example, we examine the consequences of environmental flow policies designed to regulate the timing of diversions and reservoir filling. As described previously, the proposed environmental flow policy for northern California restricts diversions in the winter, such that impacts to downstream flows are greatly reduced. This is because, in most cases, flows exceed the minimum threshold only a few days over the winter. Because the diversion period is greatly reduced, the impact index calculated for all but one of the reservoirs under the proposed policy scenario drops to <0.05 km day (in contrast to the impact values shown in Table 2). While the policy

Table 2 Characteristics of hypothetical pond storage locations (A–N) and priority based on benefit-to-impact (% of catchment storage-to-impact index) ratio

Pond	Pond capacity (10^3 m^3)	Storage benefit (% of total catchment water storage)	Storage impact (impact index, km day)	Benefit-to-impact ratio (weighted ratio, 1000 × % km^{-1} day^{-1})	Pond priority
A	33.2	6.5	11.5	5.7	1
B	10.8	2.1	6.2	3.4	2
C	32.6	6.4	46.5	1.4	8
D	13.9	2.7	22.2	1.2	11
E	12.8	2.5	8.1	3.1	3
F	17.1	3.4	16.1	2.1	7
G	108.5	21.4	90.8	2.4	6
H	134.2	26.4	104.7	2.5	5
I	59.5	11.7	39.7	3.0	4
J	17.2	3.4	51.2	0.7	14
K	14.1	2.8	33.4	0.8	13
L	23.4	4.6	41.8	1.1	12
M	13.5	2.7	19.6	1.4	10
N	16.9	3.3	24.2	1.4	9

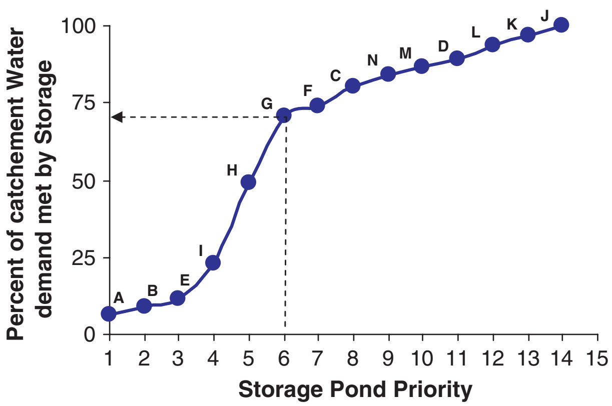

Fig. 3 Cumulative water storage capacity in catchment by pond priority, based on their benefit-to-impact ratio. Dashed line indicates that approximately 70% of total basin water demand could be met by installing the 6 highest-priority storage ponds.

significantly reduces potential impacts of storage to winter environmental flows, the restriction on diversions also reduces the total amount of water stored over the winter (Fig. 4). A few of the ponds (e.g. G, H and L) fill completely, whereas others (e.g. D) receive no water because flows at the location failed to exceed the minimum threshold over the water year. Overall, approximately 60% of the total basin water demand would be met under the environmental flow protection policy if all 14 water storage ponds were installed, suggesting that agricultural irrigation needs would have to be met by diverting water during the summer months.

Applications & next steps

Despite the complexity and multiplicity of natural and anthropogenic stressors on river ecosystems in Mediterranean climates, it is possible to reduce potential ecological impacts and improve our management of water resources to meet both human and ecosystems needs. The model we propose supports an integrated approach to water management by accounting for the spatial and temporal variability in water availability, human water needs and environmental flow requirements. In addition, the model allows for the analysis of cumulative impacts, which are often difficult to quantify but may be a significant cause of ecosystem degradation in decentralised water management systems. Furthermore, the modelling framework can help to prioritise freshwater conservation efforts by evaluating the impacts and benefits of changes in water management practices on environmental flows. Finally, this framework makes it possible to assess the consequences of alternative policy scenarios and supports integrated decision-making by institutions responsible for water and freshwater ecosystem management.

Our model is focused on the management of surface flow in rivers and streams, because in Mediterranean-climate regions they are the critical limiting resources for meeting human water needs and sustaining ecological functions. However, in some locations ground water is also important for meeting water needs, and the extraction of ground water has the

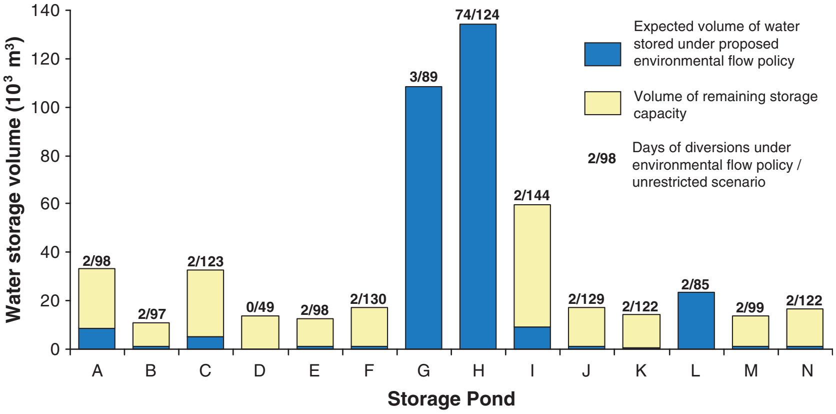

Fig. 4 Volumes of water stored under an environmental flow policy that restricts period of diversions to allow for fish migrations. Numbers above bars indicate the number of days that water could be diverted from streams to fill ponds under the environmental flow policy and when diversions are unregulated. When winter flow diversions are not restricted, all ponds are filled to capacity.

potential to reduce surface flows and impact stream biota (Spina *et al.*, 2006; Dewson *et al.*, 2007). We expect future iterations of the model to incorporate surface water–ground water interactions to improve our predictions of streamflow and water availability. We also plan to incorporate additional complexity in the model by considering other drivers of human water use practices, including water rights, land values and local site topography.

Because our existing model does not include spatial variation in channel morphology and habitat conditions, an important future extension of the model will be to explicitly link the predictions of flow alterations with ecological impacts. Such an advancement would require a higher-resolution digital elevation model that captures changes in channel morphology within the drainage network, riparian vegetation structure, the spatial distribution of target species/assemblages and their responses to changes in flow (e.g. based on hydraulic preferences). However, these data are currently not available over the large spatial scales that the model is designed to analyse. Nevertheless, model impact predictions could inform reach-scale studies on the potential ecological effects of flow alterations through the application of instream habitat models, such as Physical Habitat Simulation (PHABSIM) or other environmental flow methodology (Tharme, 2003). Ideally, such research efforts could be integrated with a broader framework to improve the knowledge of links between flow dynamics and biotic assemblage responses and guide water management decisions (e.g. Souchon *et al.*, 2008).

Ultimately, the effectiveness of this model as a decision-support tool will be largely determined by the institutional capacity to conduct impacts analysis and develop management strategies at appropriate scales. This requires a formalised, integrated decision-making process and legitimate legal/political authority that are deficient both in Mediterranean and non-Mediterranean countries. Coordinated cross-governmental agency efforts will be needed to conduct catchment-scale assessments and more importantly to implement resulting planning priorities. Moreover, landowner participation and support will be critical for the success of this coupled human and natural systems approach to water management. Therefore, we agree that a collaborative approach encouraging participatory research is necessary, as has been described for developing environmental flow recommendations by Richter *et al.* (2006).

Discussion

Freshwater ecosystem management and restoration, and environmental problem solving in general, will not result in the desired effects if the biological, physical or social impacts, and benefits are considered in isolation. Integrated approaches from multiple perspectives and disciplines are required (King, Brown & Sabet, 2003). The approach we illustrate by the examples presented, and in our larger effort to increase our understanding of the coupled natural and human Mediterranean-climate watershed system, takes advantage of hydrologic modelling tools that make it possible to represent the spatial and temporal dynamics of human water use and ecological flow requirements. This approach would not be possible without the collaboration of hydrologists, economists, biologists and social scientists that has been fostered at our research institution (University of California, Berkeley) and that is increasingly being recognised as important in emerging interdisciplinary environmental science departments worldwide.

Likewise, interactions with landowners and policy makers through an active, participatory research programme in northern California has been critical to our progress and is allowing us to move our models and exploration of hypothetical case studies from theory to practice. The early adopters of our decision-support tools are the rural landowners who have not been able to achieve water security or certainty in dealing with endangered species regulations. In contrast, resource institutions are more entrenched in their existing paradigms regarding impacts associated with multiple stressors and tend to avoid integrated approaches to environmental problem solving by relying on narrow definitions of their jurisdiction or regulatory responsibilities. At least in part, this is the result of a lack of resources to address the full complement of issues and cumulative impacts in particular.

As in other Mediterranean-climate regions, agriculture in California is responsible for around 80% of total water use. This has led many to argue that improvements in agricultural water use efficiency are necessary to meet the growing demands of other water users (e.g. urban and environmental) (Cooley, Christian-Smith & Gleick, 2008). However, in our setting, the irrigation efficiency of vineyards is relatively high; therefore, improvements in efficiency are unlikely to yield significant gains in supply for other uses. Therefore, we must consider other ways to secure supplies for ecosystem needs. We acknowledge that the expansion of winter storage capacity to meet human water demands is a potentially controversial view given the ecological impacts caused by impoundments. In contrast to the position of reducing total consumptive uses through aggressive water-saving measures (e.g. fallowing agricultural lands and preventing further land development), we advocate a more pragmatic approach for managing the use of water. While recognising the importance of water conservation efforts, we believe that there is probably some optimal storage capacity in a given watershed that will satisfy a significant proportion of human demands while maintaining adequate streamflows to protect environmental benefits. Some level of water storage development in Mediterranean-climate regions is not only appropriate, it is probably necessary for the long-term protection of freshwater ecosystems.

Our framework for streamflow management is relevant to freshwater ecosystem conservation in other climate regions. Global climate change is likely to result in greater uncertainty in natural water supplies in both Mediterranean and temperate climates (Araus, 2004; Bonada *et al.*, 2007a). Shifts in patterns of water availability may exacerbate current water management challenges arising from population growth and environmental degradation. In many regions, climate change will probably reduce the resilience of ecosystems to natural and human disturbances and further constrain freshwater ecosystem management. Thus, approaches to sustainable water management in highly variable-climate systems (such as Mediterranean regions) may become increasingly useful in other regions as the effects of climate change become evident.

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Conflicts of interest

The authors have declared no conflicts of interest.

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