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EVALUATING TRADEOFFS BETWEEN ENVIRONMENTAL FLOW PROTECTIONS AND AGRICULTURAL WATER SECURITY

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ABSTRACT

River basin managers responsible for water allocation decisions are increasingly required to evaluate tradeoffs between environmental flow protections and human water security. However, the basin-scale effects of environmental flow regulations on water users are not well understood, in part because analyses are complicated by the spatial and temporal variation in water availability, human demands, and ecosystem needs. Here, we examine alternative regional environmental flow policies and their effects on a distributed network of water users in a small (182 km^2) river basin in coastal California. We use a hydrologic model to simulate water diversion operations under three policy scenarios and quantify potential impacts to bypass flows for adult migrating salmon and agricultural water storage. The results indicate that there are inherent tradeoffs between environmental flows and agricultural water security, with the most restrictive environmental policy associated with the greatest impacts to water users. Surprisingly, the moderate environmental flow policy had larger impacts to bypass flows than the unregulated management scenario, suggesting that ecological benefits of the moderate policy are small relative to the adverse effects on agricultural water users. Conflicts between environmental and human water needs were greatest in upper catchments (<2.5 km^2), where flow protections caused the greatest reduction in water storage. Although natural supplies were adequate for meeting water needs in most years regardless of policy restrictions, potential for conflict between environmental flow protections and water security was evident in dry years. Therefore, strategies are particularly needed for drought-year water management to ensure adequate environmental flows while reducing human water allocations in an equitable manner. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: water management; hydrologic modelling; salmon; passage flows; vineyards

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INTRODUCTION

There is growing recognition that the allocation of water for environmental purposes is essential for sustaining river ecosystems (Baron *et al*., 2002). For some river basins, environmental flow requirements have been incorporated in water management through the modification of dam operations (e.g. Moyle *et al*., 1998; Richter and Thomas, 2007) and restrictions on water withdrawals (e.g. Acreman *et al*., 2008). Nevertheless, most of the world's rivers have no or inadequate environmental flow protections and, despite efforts to reduce the cost and complexity of environmental flow determinations (e.g. Poff *et al*., 2010), the degradation of freshwater ecosystems is accelerating (Nilsson *et al*., 2005; Dudgeon *et al*., 2006; Naiman and Dudgeon, 2011). The complex nature of water management systems, which involve the interaction between economic agents, ecosystem processes, and institutional constraints, continue to limit the application of environmental flows in many regions of the world.

Arguably the greatest obstacle to environmental water allocations is reconciling conflicting human and ecosystem water needs. Water allocations to the environment often restrict other human users and thus stimulate substantial social and political conflict (Poff *et al*., 2003; Richter, 2010). While the benefits of environmental flows are shared by the public (e.g. through the provisioning of ecosystem services), the costs of environmental flow allocations are generally borne by individuals and may be distributed inequitably among water users (Loomis, 1998). These problems are intensified in water-stressed regions, where competition for water supplies is greatest and imposing any environmental flow requirement necessarily limits human water uses (Gasith and Resh, 1999). It has been estimated that nearly 80% of human populations are facing threats to water security (Vörösmarty *et al*., 2010), suggesting that the challenge of balancing human and ecosystem water allocations will continue to intensify.

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Previous studies have investigated the social and economic consequences of environmental flow allocations in water scarce regions. Many have focused on relatively large rivers in the western United States, where flow releases from large reservoirs are required for species protected under the federal Endangered Species Act (ESA). For example, in an examination of the social and institutional factors influencing water allocation decisions in the Klamath River basin, Woodward and Romm (2001) described how environmental water allocations to restore ESA-listed salmon disproportionately affected agricultural water users. Kim (2012) documented the impacts of environmental flows on municipal and irrigation water uses in the Brazos River Basin. Others have analysed the impacts of environmental flow regulations on agricultural water users in areas where large reservoirs are the primary source of water for both human uses and environmental flows, such as the Walla Walla River Basin (Willis and Whittlesey, 1998), Snake River (Green and O'Connor, 2001; Briand *et al*., 2008), and Rio Grande (Ward and Booker, 2003).

In comparison to research conducted on large regulated rivers, much less attention has been given to the effects of environmental flow regulations in decentralized water management settings. In regions where agricultural and residential water users do not have access to supplies from large reservoirs, individuals rely on small-scale projects to meet their water needs (Deitch *et al*., 2009). These small water projects are spatially distributed and include groundwater wells, runoff collection ponds, and stream diversions, which are designed to provide water to individuals at the local scale. Decentralized water management may be viewed as less environmentally damaging than large dams because impacts from individual projects are relatively small and are dispersed across the landscape (Potter, 2006). However, when multiple water diversions are operating on a common stream network, the incremental removal of water can produce significant cumulative impacts on flows. Assessing cumulative hydrologic effects (and potential consequences of environmental flow management) in branched stream networks is complicated due to spatial variation in environmental conditions and differences in operations among individual water projects (Chessman *et al*., 2011). Furthermore, river basin heterogeneity can have profound effects on environmental water needs, as well as ecological threshold responses to anthropogenic stressors (Watanabe *et al*., 2006).

Advancements in hydrologic modelling have greatly improved our ability to simulate complex water management systems and evaluate the potential effects of regulations, land use, and climate conditions (e.g. Kennen *et al*., 2008; Merenlender *et al*., 2008; Archfield *et al*., 2010, Shafroth *et al*., 2010; Sanderson *et al*., 2011). Some studies have utilized hydrologic models to explore the local and cumulative effects of spatially distributed water users on streamflows at the basin scale (Deitch *et al*., 2009; Grantham *et al*., 2010). However, the consequences of regional environmental flow regulations on individual water users, and how threats to water security are distributed among them, have not yet been evaluated, in part because of the complexity involved in analysing decentralized water management systems. Quantifying the tradeoffs between environmental protection and agricultural water security is critical to water-scarce regions where increased environmental flow protections may have significant and inequitably distributed impacts among water users.

In this study, we explore the tradeoffs between environmental flow protections and agricultural water security based on alternative water management policies, recently proposed and/or implemented to provide environmental flows for anadromous fish in an agricultural region with decentralized water management. We focus on a small river basin in coastal California, where listing of salmon populations under the federal ESA in the 1990s has led to increasingly stringent regulations of water diversions by the state. Vineyards represent the dominant agricultural use in the region and have been most affected by changes in regulations because they primarily rely on diversions from salmon-bearing streams to meet their water needs. In some cases, vineyard owners divert and store water in off-stream ponds during the wet, winter months, which provide a reliable supply of water throughout the dry irrigation season. However, regulations to protect salmon streams have led to an effective suspension of new permits to divert and store water, and as a consequence, fewer storage ponds have been constructed relative to estimated demands (Newburn *et al*., 2011). In 2010, the State Water Resources Control Board (SWRCB) adopted a regional instream flow policy that established new guidelines for permitting on-stream diversions in coastal streams in northern California (SWRCB, 2010). The policy sets restrictions on water diversions in order to protect minimum flows required for adult salmon upstream migration and spawning. It also establishes guidelines for evaluating requests for new appropriate water storage rights, which could lead to the development of additional storage ponds in the region. Although the regulations establish diversion limits for protecting environmental thresholds, permitting new diversions would increase pressures on streams in the region, potentially impairing ecosystems as well as affecting existing water users. At the same time, there is concern that new environmental flow regulations could limit the ability of agricultural water users to meet their water needs. To this point, no evaluation has been conducted to assess the effectiveness of the regulations in providing regional protections of salmon migration flows or their implications for agricultural water security.

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Our overall objective is to quantify the tradeoffs between environmental flow protections and agricultural water security at the basin scale, accounting for the spatial and temporal variation in water availability, the needs of agricultural water users, and ecological flow requirements. This is the first attempt to evaluate the simultaneous effects of environmental water policies on ecologically relevant flow metrics and agricultural water users in a decentralized water management setting. First, we map the distribution of vineyards and storage ponds to assess the level of agricultural water demands in the river basin. We then use an econometric model to quantify the need for additional water storage that has not been permitted due to regulatory constraints. Next, we use a hydrologic model to quantify the potential impacts of alternative management scenarios on environmental flows and agricultural water security over a range of inter-annual rainfall variability. Specifically, we assess (i) the impacts of agricultural water diversions on ecologically relevant flow metrics (e.g. number of days in which flows provide for the upstream migration of salmon), (ii) the effects of unpermitted water users on the water security (e.g. volume of seasonal water needs met) of permitted water users under alterative management scenarios, and (iii) tradeoffs between environmental flow protections and agricultural water security. Analyses such as these are critical for supporting integrated water management and for developing effective and equitable strategies for allocating water between human and ecosystem needs.

STUDY AREA

Maacama Creek watershed

The study focuses on the Maacama Creek watershed, located in the eastern portion of the Russian River basin in Sonoma County, California (Figure 1). Maacama Creek and its tributaries occupy a 182-km^2 drainage basin, situated on the western slope of the Maacama Mountains, which extends from 40 m above sea level (asl) at the confluence with the Russian River to over 1000 m asl. The region is characterized by a Mediterranean-type climate, with the majority of rainfall occurring in the cold winter months (November to March), followed by a dry period that extends through the summer and fall. Streamflows correspond to precipitation patterns, with peak winter flows exceeding base flows by several orders of magnitude. Flows generally recede throughout the spring to approach or reach intermittency by the end of the summer. Mean annual discharge for Maacama Creek is approximately 2.3 m^3 s^{-1}, based on 20 years of daily records (1961–1980), with mean monthly flows ranging from 0.2 m^3 s^{-1} (in September) to 5.8 m^3 s^{-1} (in February).

Management context

The region is known for its premium wine grape production, and vineyard agriculture is the dominant water user in the Maacama Creek watershed. Most moderately size catchments (>100 km^2) in Sonoma County support less than 5% vineyard land use (Lohse *et al*., 2008; Grantham *et al*., 2012), which is generally restricted by the steep topography and limited road access. In the Maacama Creek watershed, there are approximately 14.2 km^2 of vineyards, occupying 7% of the watershed (Figure 1). Agricultural and domestic water users in the basin do not have access to services from large water projects (e.g. water storage and conveyance from major reservoirs). Rather, water users are largely dependent on regional precipitation, which is collected by surface water diversions and shallow groundwater wells (Deitch *et al*., 2009). In addition, many vineyards have small {<200 000 m^3 [100 acre-feet (af)]} storage ponds which collect rainfall–runoff and may be filled by surface water diversions. In order to divert and store water for agricultural use, landowners must apply for an appropriative water rights permit from the SWRCB. While the SWRCB has permitted over 2500 water diversions from streams in the 3800 km^2 Russian River basin (Deitch *et al*., 2009), the approval of new water rights has decreased due to legal challenges and concerns over impacts to ESA-listed salmon. As a consequence, since the listing of salmon under the ESA in the mid-1990s, many landowners have been unable to obtain water rights for diversions, and the number of new reservoirs built on vineyard properties has fallen significantly (Newburn *et al*., 2011). Other landowners have proceeded to construct small reservoirs and illegally divert from streams without water right permits.

To protect flows needed for the upstream migration of ESA-listed salmon, the SWRCB has imposed increasingly stringent conditions on new water rights applicants for winter diversions. Guidelines implemented in 2002 (herein the ‘moderate policy’) restricted new diversions to periods when streamflows exceeded the estimated unimpaired February median flow (Q_{fmf}) at the point of diversion (POD) (CDFG and NMFS, 2002). The month of February generally experiences higher flows relative to other months and thus provides a reference for setting flow thresholds for adult salmon migration. The more recent Northcoast Instream Flow Policy (SWRCB, 2010) (herein the ‘strict policy’) generally sets a higher diversion threshold for new water rights permit applicants than the moderate policy. This minimum bypass flow (Q_{mbf}) threshold is defined by an empirically derived regional relationship of flow and water depths needed for fish passage (e.g. 0.8 m). Both the moderate and strict policies require that diversions occur between 15 December and 31 March (herein the ‘diversion season’). Water rights permits issued before 2002 generally do not

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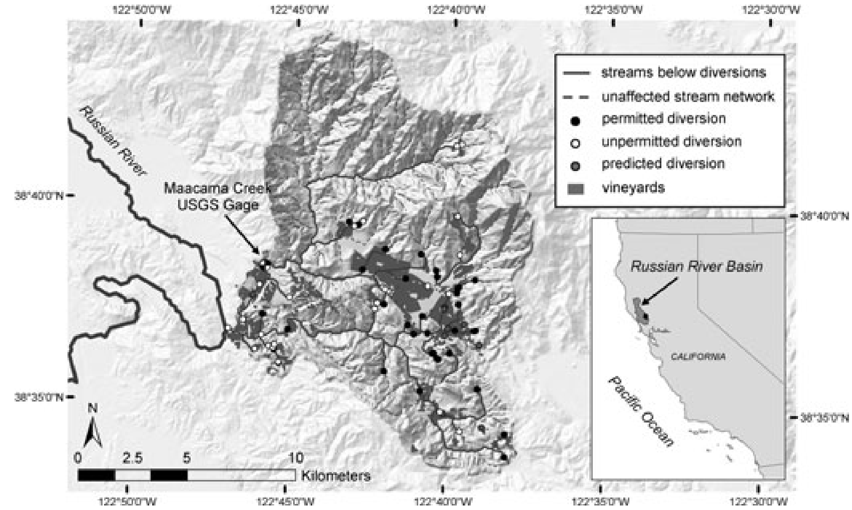

Figure 1. Points of diversion (PODs) for vineyard agriculture in the Maacama Creek watershed, Sonoma County, California.

have conditions for protecting salmon passage flows and allow for the diversion of all winter streamflow at a POD needed to meet reservoir water storage needs (herein the 'unregulated policy') (Figure 2). However, these water use operations have been subject to increasing pressure from government agencies to limit potential impacts to ESA-listed salmon, and as a consequence, some pre-2002 water rights holders have begun to adopt practices consistent with the environmental flow policies.

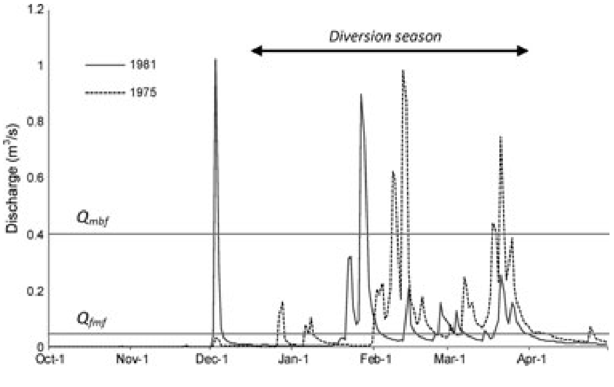

Figure 2. Hydrographs for normal (1975) and normal-dry (1981) rainfall years at a point of diversion in the upper Maacama watershed (drainage area of 3.6 km^2). When subject to environmental flow regulations, water withdrawals are restricted to the diversion season (15 December to 31 March) and are only permitted when flows exceed February median flow (Q_{fmf}) for the moderate policy and the minimum bypass flow (Q_{mbf}) for the strict policy. Under the unregulated scenario, all flow can be diverted at the POD until reservoirs are filled to capacity.

METHODS

Water storage demands

To estimate the demand for water storage by individual landowners in the Maacama Creek watershed, we first developed a geographic information system (GIS) to map vineyard and water storage ponds at the parcel level. Vineyard land cover was digitally mapped from orthorectified high-resolution aerial photos from 1973, 1993, and 2006. Reservoirs were also digitally mapped from aerial photographs, and the measured surface area was used to estimate total volume based on an empirical relationship derived from a subset of reservoirs of known surface area and volume ($n = 100$). All vineyards and reservoirs were assigned to individual landowners based on parcel boundaries obtained from the Sonoma County Tax Assessor's Office. Where adjacent parcels were owned by the same vineyard landowner, the parcels were combined in a single property to reflect a common management unit. The total water storage demand for a vineyard landowner was calculated as the total volume of all reservoirs present on the parcel(s). In addition, we reviewed the SWRCB water rights database to determine which landowners in the Maacama watershed had an approved appropriative right for onsite storage, allowing us to classify all vineyard landowners with reservoirs as 'permitted' or 'unpermitted.'

Due to the increased difficulty in obtaining water rights since the 1990s (Newburn *et al*., 2011), it is likely that some vineyard landowners have been unable to build onsite reservoirs despite the need for additional water storage. To predict the locations of additional onsite storage likely to be built in a more permissive regulatory system, an econometric model was developed using parcel attributes and previous landowner decisions to build vineyards or reservoirs. The

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bivariate probit model (described in Newburn *et al*., 2011) characterizes landowner behaviour before ESA listing, prior to the more stringent restrictions on water rights permitting. The econometric model assumes that a landowner makes two discrete-choice decisions on land use (build vineyard or not) and water management (build reservoir or not), based on the physical characteristics of the parcel (e.g. slope, geology, climate, riparian access) and economic factors such as proximity to transportation corridors. The econometric model was parameterized using data from all landowner reservoir and vineyard construction decisions made in Sonoma County during the period from 1973 to 1993, prior to restrictions on water rights permitting.

Each of the 58 properties in the watershed greater than 0.04 km^2 (10 acres; 4 hectares) and with more than 4000 m^2 (1 acre) of vineyard but no water storage was assigned a reservoir when the conditional probability of reservoir development (estimated by the model) exceeded a single random number (between 0 and 1) generated for each property. These additional reservoirs were placed at the point in the landowner property with the largest catchment area and specified with a storage capacity (in acre-feet) equal to two-thirds of the vineyard acreage, a standard estimate of annual vineyard water needs (Merenlender *et al*., 2008). The potential for vineyard expansion (and associated growth in water demands) was not evaluated. Vineyards are generally restricted to moderate slopes (0–10%), and for the Maacama Creek watershed, nearly all vineyards (90%) occur on slopes less than 20%. These moderately sloped areas occupy less than 20% of the watershed, and most have already been developed by vineyards or residential land use. The vast majority of the watershed (>80%) has slopes greater than 20% and therefore has limited potential for vineyard development.

Streamflow modelling

We used the Streamflow Impacts GIS-based (SIG) model to predict the hydrologic effects of water diversions and environmental flow regulations on streamflows. The SIG model is designed to assess the hydrologic impacts of distributed networks of water users at ecologically meaningful scales (Merenlender *et al*., 2008). The model is capable of running various water years, estimating the extent of flow impairment throughout the stream network in relation to specific flow thresholds, and calculating the amount of water stored within reservoirs over time. Alternative diversion rules (e.g. timing and rates of withdrawal) can also be specified to reflect changes in water management operations and/or regulatory requirements.

The model requires a high-resolution digital elevation model (DEM) of the study area, a nearby flow gauge with daily streamflow records, precipitation data, and the locations and operational rules of water diversions. For the Maacama Creek basin, a 10-m resolution DEM was used to define the stream routing network using Arc Hydro Tools in ArcGIS 9.3 (ESRI, 2009). Estimates of daily flows were derived from 20 years of gauge data (1961–1980) on Maacama Creek (USGS Station #11436900). These data are scaled by catchment area and precipitation in order to estimate unimpaired daily flows within all streams segments in the drainage network over the 20-year period of record. For presentation purposes, each of the water years was ranked based on total annual rainfall and classified by quartiles into dry (rank 1–5), normal-dry (rank 6–10), normal-wet (rank 11–15), and wet (rank 16–20) years. All parcels with reservoirs were assigned a POD. If a stream was present on the parcel, the POD was located at the stream segment closest to the reservoir. If not, the POD was located at the lowest point on the reservoir. When the model is run, water is diverted at each POD under the operational rules of the specified regulatory scenario. Once reservoirs are filled, no additional diversions occur at the POD.

Effects of regulations on streamflows

We first used the hydrologic model to evaluate the effects of three regulatory scenarios (unregulated, moderate environmental flow policy, and strict environmental flow policy) on streamflows downstream of diversions for 20 water years. Reservoirs are assumed to be empty at the start of the water year (1 October). Under the unregulated policy, diversions are operated with no restrictions and all streamflow is captured at the POD until the end of the salmon migration period (30 April) or until the reservoir fills to capacity. Once a reservoir is filled, all flow at the POD continues downstream. Under the moderate policy, flows must exceed the February median flow (Q_{fmf}) threshold at the POD before diversions are allowed, at which point all flow above Q_{fmf} can be captured to fill reservoirs during the diversion season (Figure 2).

Under the strict policy scenario, the regulations distinguish diversions located above and below the end of anadromy (EOA), the upper limit of potential spawning habitat for salmonids. The EOA was defined for all streams in the GIS for Maacama watershed by identifying locations where the longitudinal gradient of the stream channel is 12% or greater over a distance of at least 100 m (SWRCB, 2010). For PODs located above EOA, the strict scenario uses Q_{fmf}, although the actual policy allows for exceptions to this depending on site characteristics. For diversions below EOA, the minimum bypass flow threshold (Q_{mbf}) is more restrictive than Q_{fmf}, and is defined by the formula

$$Q_{mbf} = 9.0\ \ Q_m, \tag{1}$$

for PODs with upstream drainage areas of 1 mi^2 (2.6 km^2) or smaller, and

$$Q_{mbf} = 8.8\ Q_m(DA)^{-0.47}, \qquad (2)$$

for PODs with drainage areas greater than 1 mi^2 (2.6 km^2), where Q_{mbf} equals the minimum bypass flow in cubic feet per second ($\mathrm{ft}^3\,\mathrm{s}^{-1}$; $1\,\mathrm{ft}^3\,\mathrm{s}^{-1} = 0.03\,\mathrm{m}^3\,\mathrm{s}^{-1}$), Q_m equals the mean annual unimpaired flow (in $\mathrm{ft}^3\,\mathrm{s}^{-1}$), and DA equals the drainage area in square miles upstream of the POD.

To evaluate the impacts of diversions on downstream flows under the alternative policy scenarios, we focused on two ecologically relevant flow metrics. First, we calculated the number of days for each water year that flows would be expected to exceed the minimum bypass flow threshold (Q_{mbf}) under unimpaired conditions (i.e. no diversions) during the migration season (1 November to 30 April). We calculated the change in the number of potential bypass days relative to unimpaired conditions as a result of water withdrawals, restricting the analysis to affected streams below EOA (where migrating salmonids could potentially occur). Secondly, we calculated the loss of streamflow resulting from diversions as a percentage of expected unimpaired flows at all stream segments downstream of diversions. We considered both the spatial variation in impacts (differences in the magnitude and frequency of flow impairment by location in the watershed, or drainage area) and temporal variation in impacts (for 20 water years in which the timing and magnitude of precipitation vary).

Effects of regulations on agricultural water security

To evaluate the effects of the environmental flow policies on agricultural water security, we calculated the percentage of water stored in each vineyard reservoir relative to total storage capacity. Similar to the impacts assessment for ecological flow metrics, we considered the spatial and temporal variation in water storage patterns by watershed location and water year, respectively. We first evaluated the ability of water users to meet their water storage needs under each of the three policy scenarios. Next, we quantified the potential effects of new water diversions on landowners with existing, permitted diversions. Finally, we considered tradeoffs between impacts to ecologically relevant flow metrics and agricultural water security under the unregulated, moderate, and strict policies.

RESULTS

Agricultural water demands

A total of 61 reservoirs on vineyard properties were identified in the Maacama Creek watershed. The reservoirs vary in size, with an estimated mean capacity of 34 600 m^3 (28 af) and a range of 617–207 224 m^3 (0.5–168 af). Based on State records, 35 of the reservoirs are located on parcels with permitted water rights, while the remaining 26 reservoirs do not appear to have water rights registered with the State Water Board (Figure 1). The PODs for each reservoir are distributed throughout the Maacama watershed and have an average upstream drainage area of 12.1 km^2 (4.7 mi^2) ranging from 0.1 to 181 km^2 (0.04–70 mi^2). The economic model predicted that there is demand for an additional nine reservoirs on parcels with vineyards in the Maacama watershed (Figure 1). The new reservoirs represent an additional 226 000 m^3 (183 af), or 11%, of water storage already provided by existing vineyard reservoirs [2 100 000 m^3 (1711 af)] in the watershed.

Environmental flow impacts

The number of days in which adult salmon could potentially migrate through the Maacama Creek watershed (in the absence of water diversions) was calculated for all 10-m segments of the drainage network below the EOA for 20 water years. The total number of days that flows exceeded the salmon bypass flow threshold varied by catchment area and by annual variation in flow patterns (e.g. timing, frequency, and magnitude of high flows). The number of salmon bypass flow days was generally greater in the lower watershed (e.g. larger streams) than in the upper watershed (e.g. small streams). For example, in 1981 (normal-dry year), streams in the upper watershed [<2.5 km^2 (<1 mi^2) catchment] had flows that exceeded the bypass threshold for only 4 days on average, while stream reaches in the lower watershed [>25 km^2 (>10 mi^2)] had suitable fish passage flows for over 25 days (Figure 3). This pattern was consistent for all water years and is explained by the non-linear relationship between the bypass flow threshold and drainage area [Equations (1) and (2)]. The total number of bypass days within the stream network also varied substantially among years. In dry years, the average number of bypass days across the stream network was 5.3 days, while in wet years, the average number of bypass days was 40.5 (Table I).

The hydrologic impacts of water diversions were considered by running the SIG model with the 70 vineyard reservoirs and associated PODs (Figure 1). Streamflow impacts were assessed under three policy scenarios (unregulated, moderate, and strict) for 20 water years by calculating (i) the number of bypass flow days lost (relative to unimpaired conditions) and (ii) the percentage of flow reduction at each stream segment. The drainage network affected by diversions (e.g. occurring downstream of PODs) included 100.9 stream km (62.7 mi), representing 34.9% of the total stream length in the Maacama watershed. All stream segments with large catchment areas (>25 km^2) were affected by upstream diversions [total length of 30.5 km

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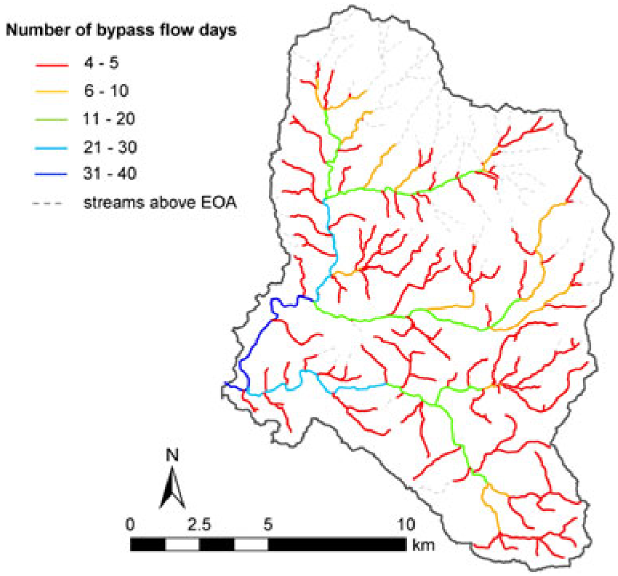

Figure 3. Number of salmon bypass flow days in the Maacama watershed for all stream segments below EOA in a normal-dry year (1981) under unimpaired conditions.

(19.1 mi)], while less than 20% of streams [33.8 of 183.6 km (21 of 114 mi)] in small catchments (<2.5 km^2) were affected (Figure 1). However, impacts to flows in small streams tended to be greater than for larger streams, expressed as both the loss of bypass days and magnitude of flow reduction (Table II). For example, under the unregulated policy, streams in small catchments lost an average of 0.8 bypass days, representing 9.1% of total bypass days relative to unimpaired conditions. In comparison, basins in moderate (2.5–25 km^2) and large catchments (>25 km^2) lost an average of 0.3 (3.9%) and 0.6 (2.2%) bypass days, respectively. For the unregulated policy, the average reduction in flow for affected streams within small catchments was 12.0%, compared to less than 4.0% for affected streams with larger catchment areas (Table II).

Table I. Average number of bypass flow days[a] under unimpaired conditions and three regulatory scenarios, by water-year class

	Dry[b]	Normal-dry	Normal-wet	Wet
Unimpaired	5.3	19.0	28.7	40.5
Strict	5.3	18.9	28.6	40.5
Moderate	5.0	18.3	28.1	39.8
Unregulated	5.0	18.4	28.1	39.8

[a] Bypass flow days are calculated as the number of days in which discharge exceeds the minimum bypass flow (Q_{mbf}), calculated at each stream segment. Values are averaged over all stream segments affected by diversions below the end of anadromy.

[b] Water-year class based on ranking of annual precipitation for 20 water years. ‘Dry’ represents the average of the lower quartile of years, ‘Normal-dry’ the second quartile, ‘Normal-wet’ the third quartile, and ‘Wet’ the upper quartile.

Impacts to bypass flow days and percentage of streamflow reduction were lowest under the strict policy (Table II). The strict policy limits bypass flow impacts to 0.02 days, averaged over all years, representing only a 0.1% reduction in bypass flow days compared to unimpaired conditions. Impacts to bypass flow days were greater under the alternative policy scenarios, but notably, the moderate policy had slightly greater average impacts (0.58 days) than the unregulated scenario (0.55 days) (Table II). This can be explained by the diversion season restriction of the moderate policy. When diversions are unregulated, water diversions operate as soon as flowing water is available and thus can capture early season (October and November) flows. As a consequence, reservoirs fill more quickly when unregulated in comparison to the moderate and strict policy scenarios, for which diversions are delayed until 15 December, prolonging the period of reservoir filling. While the strict policy effectively preserves bypass flows, the moderate policy is less protective and, on average, has the greatest impacts to bypass flow days. For example, in 1981 (normal-dry year), seasonal impacts to bypass flows days are greatest for the moderate policy and slightly less under the unregulated scenario (Figure 5). There is essentially no loss of bypass flows days under the strict policy. Both the strict and moderate policies limit seasonal streamflow losses in comparison to the unregulated scenario (Table II). However, diversions operating under the unregulated and moderate policy scenarios show similar spatial patterns of impact, while the reduction of streamflow under the strict policy is notably less (Figure 4).

The impacts of water diversions on streamflow metrics varied among water years. The magnitude of bypass flow impacts generally increased with wetter years, although when expressed relative to unimpaired conditions, bypass flow impacts were greatest in the dry years (Table I). The average reduction in streamflow (expressed as percentage of loss relative to unimpaired conditions) decreased with increasingly wet years (Figure 5). The largest differences in streamflow impacts among the policy scenarios occurred in dry years. For the driest year (1977), the moderate and strict policy scenarios had no loss in streamflow because the diversion bypass thresholds were never met (e.g. natural flows never reached levels sufficient for upstream salmon migration). However, for the unregulated policy, there was a 30% average reduction in streamflows relative to unimpaired conditions. The average percentage of loss in flow converged by the sixth driest water year (1979) for the moderate and unregulated policies (Figure 5), indicating that similar volumes of water are diverted from streams in non-dry years (i.e. those above the lower quartile). The strict policy, however, had lower streamflow impacts than the moderate and unregulated scenarios for all but wet years (upper quartile), during which period the percentages of streamflow reductions were similar for all three scenarios (Figure 5).

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Table II. Impacts to bypass flow days and streamflow for three regulatory scenarios by watershed area and averaged over all water years (1961–1980)

	Bypass flow days[a]				Percentage of natural streamflow			
	<2.5 km^2	2.5–25 km^2	>25 km^2	Average	<2.5 km^2	2.5–25 km^2	>25 km^2	Average
Unimpaired	8.6	19.1	44.3	23.4	100	100	100	100
Strict	8.5	19.1	44.3	23.4	96.5	98.7	98.8	98.0
Moderate	7.7	18.7	43.8	22.8	93.3	97.9	98.1	96.4
Unregulated	7.8	18.8	43.7	22.8	88.0	96.1	96.5	93.5

[a] Number of days in which flow exceeded the minimum bypass threshold (Q_{mbf}) for upstream migration of salmon, assessed for all affected streams below the end of anadromy.

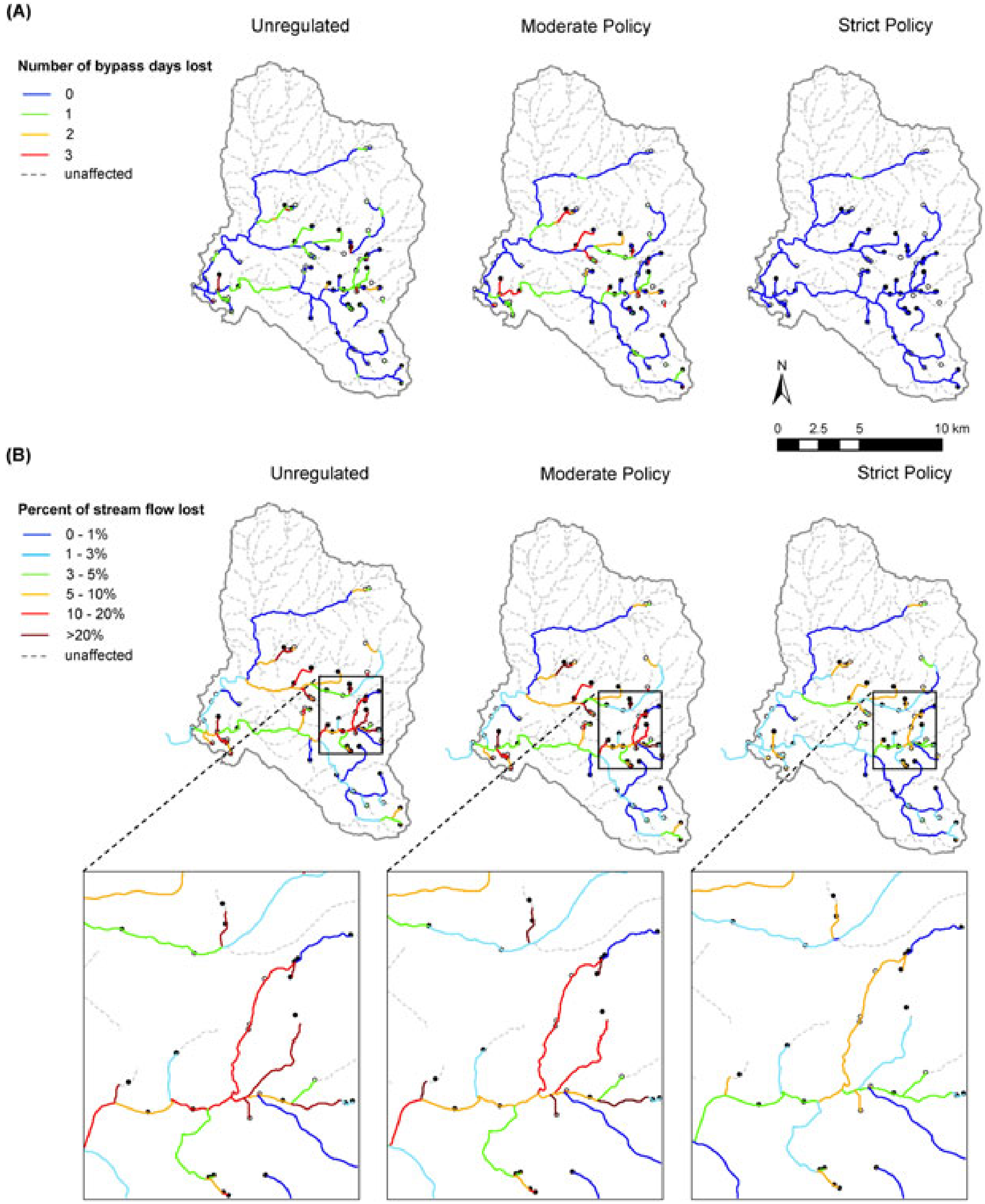

Figure 4. Number of salmon bypass flow days lost (A) and percentage of flow reduction (B) under three policy scenarios for a normal-dry rainfall year (1981).

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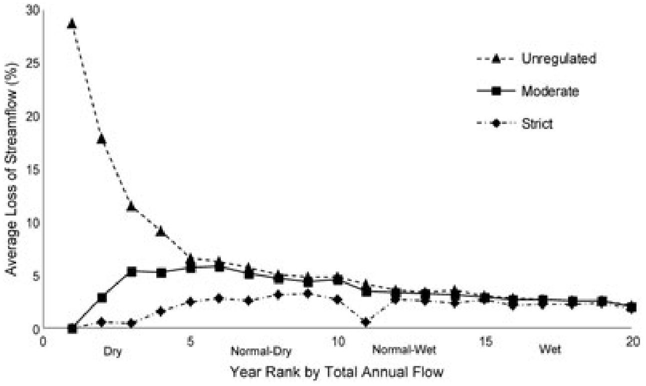

Figure 5. Average reduction in flow for streams below water diversions under the strict, moderate, and unregulated policy scenarios, by water year.

Water security impacts

The influence of environmental flow regulations on agricultural water security was evaluated by comparing the percentage of water stored relative to reservoir capacity under each policy scenario. When diversions are unregulated, the ability of water users to fill their reservoirs is influenced by the reservoir capacity, natural water supplies (e.g. rainfall in a given water year and location in watershed) and activity of upstream diverters. For vineyards in the Maacama watershed, there appear to be sufficient natural supplies to fill reservoirs to capacity in all but the driest years (Figure 6), indicating that water users meet their needs regardless of watershed location or presence of upstream water diversions.

Reservoir water storage was reduced under the moderate and strict environmental flow policies because water users are only able to divert when flows exceed the bypass flow thresholds at the POD during the diversion season. The moderate policy lowered the total volume of water stored by 20–50% in dry years relative to the unregulated scenarios, although in all other years, water users were still able to fill their reservoirs close to full capacity (Figure 6). In dry years, water users with small drainage areas at the POD tended to have lower percentages of storage than water users in large drainage area under the strict and moderate policies (Figure 7). However, spatial patterns in storage were also influenced by reservoir capacity because larger reservoirs are less likely to fill than smaller reservoirs. Under the moderate policy, reservoirs less than 12 500 m^3 (approximately 10 af) filled to 90% of capacity on average, while large reservoirs [>60 000 m^3 (50 af)] only filled to 79% of capacity (Table III).

The strict policy reduced the volume of water stored relative to the moderate and unregulated scenarios in most water years (Figure 6). Water storage under the strict policy was on average 56% lower than the unregulated scenario in dry years, 20% lower in normal-dry years, and 17% lower in normal-wet years. In wet years, reservoirs were able to fill near capacity even under the strict policy. A deviation from the trend of increasing percentage of water storage with increasing annual rainfall was observed in 1971 (rank 11) (Figure 6). This can be explained by the specific timing and

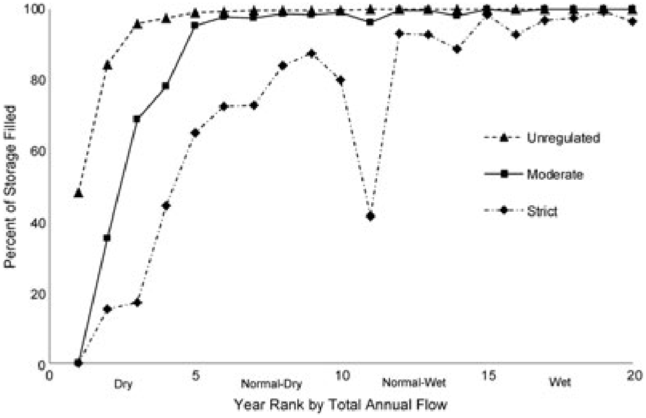

Figure 6. Average percentage of total reservoir storage capacity filled under the strict, moderate, and unregulated policy scenarios, by water year.

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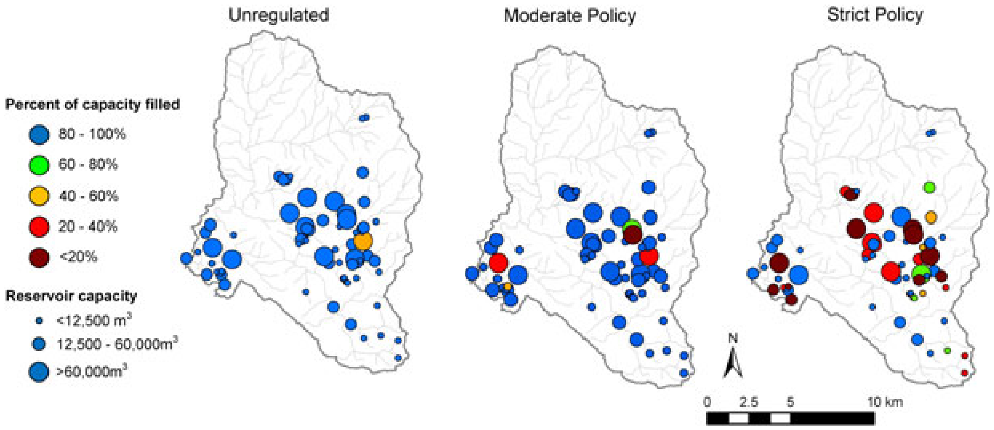

Figure 7. Water volume stored as percentage of total storage capacity under three policy scenarios for a normal-dry year (1981).

magnitude of winter peak flows, which in 1971 occurred prior to the permitted diversion season beginning on 15 December. Thus, although total annual rainfall was high that water year, the diversion of high flows early in the winter was not permitted, such that total seasonal storage was lower than otherwise expected. The effects of the strict policy on water storage were heterogeneously distributed among water users and varied by reservoir location and size. Landowners with PODs in small catchments experienced the greatest reduction in percentage of storage (from 95.0% under unregulated conditions to 66.0% under the strict policy), while the percentage stored in reservoirs with large catchments at the POD was greater than 95.0% for all policies (Table III). The strict policy also disproportionately affected large reservoirs [>60 000 m^3 (50 af)], with the average percentage of storage decreasing from 91.0% under the unregulated policy to 53.8% under the strict policy (Table III).

The presence of upstream diversions can reduce the amount of water available to downstream diverters. In particular, unpermitted water users in the Maacama watershed (35 of 70 diversions, including 9 predicted by the econometric model) have the potential to impact downstream permitted users. The percentage of water stored in existing, permitted reservoirs was calculated in the presence and absence of unpermitted water diversions to assess the potential effects of unpermitted reservoirs on the water security of permitted reservoirs. For all three policy scenarios, the potential losses in water storage were small overall, although a few permitted water users experienced large reductions in storage in dry years (Table IV). For example, in the dry years, only 2 of 35 permitted water users were affected by upstream unpermitted diversions under the strict policy, with an average reduction in storage of 4.7%. The effects were larger under the moderate policy, with 3 affected out of 35 permitted water users experiencing an average reduction of 22.3%, and under the unregulated scenario, where 2 water users lost 12.4% of water storage in dry years. The reason that impacts were lowest under the strict scenarios is because, in dry years, most water users are not able to fill their reservoirs because flows never exceed the diversion bypass threshold, thus precluding impacts to downstream users. In normal-wet and wet years, the effects of unpermitted water diversions on permitted water users were negligible (Table IV).

Tradeoffs between agricultural water security and environmental flow protections

Overall, the strict policy provided the greatest protection of bypass flow days relative to the moderate and unregulated

Table III. Percentage of storage variation by policy, reservoir capacity, and catchment area

	Reservoir capacity			Catchment area			
	<12 500 m^3	12 500–60 000 m^3	>60 000 m^3	<2.5 km^2	2.5–25 km^2	>25 km^2	Average
Strict	77.0	72.5	53.8	66.0	86.2	95.0	71.8
Moderate	90.3	88.9	78.9	86.1	93.5	95.0	88.0
Unregulated	97.4	96.6	91.0	95.0	99.2	100.0	96.1
Total Capacity	189.5	591.6	1114.5	1441.8	328.3	125.4	

Table IV. Impacts of unpermitted diversions on the permitted water users, indicated by number of affected diversions (out of 35 permitted) and percentage of water storage lost, by water-year class

	Dry		Normal-dry		Normal-wet		Wet	
	#	% loss	#	% loss	#	% loss	#	% loss
Strict	2	4.7	1	22.6	2	2.2	0	0.0
Moderate	3	22.3	0	0.0	0	0.0	0	0.0
Unregulated	2	12.4	0	0.0	0	0.0	0	0.0

scenarios (Table II) but was associated with the greatest losses in agricultural water storage (Table III). The moderate policy also limited agricultural water storage but notably provided no greater protections to bypass flow days than the unregulated scenario. The unregulated policy allowed for the highest levels of water storage but was also associated with the largest reductions in streamflow magnitudes relative to impacts under the strict scenario (Table II).

The effects of environmental flow policies on agricultural water security and salmon bypass flows varied spatially (within the watershed) and temporally (among water years). The strict policy yields 0.5 (2.3%) more bypass flow days than the unregulated policy when averaged over all affected streams and all water years. However, within small watersheds, bypass flow frequency increased by 0.7 days (8.5%), while in large watersheds, the bypass period increased by 0.6 days (1.3%), indicating that the strict policy provides greater protection of bypass flows in small, upper stream reaches than in lower reaches. Conversely, water users in small catchments experienced greater losses in storage than water users in large catchments under the strict policy. In small catchments ($<2.5\,\text{km}^2$), the average percentage of storage relative to capacity declined from 95% (under the unregulated scenario) to 66% under the strict policy, while for large catchments ($>25\,\text{km}^2$), the percentage of storage fell from 100 to 95% (Table III). Thus, the environmental flow policies disproportionately affected the water security of diverters in small catchments.

The effects of the environmental flow policies are most pronounced in dry years, when restrictions to diversions substantially reduced water storage and lessened streamflow impacts, especially in small watersheds. However, the policy restrictions did not necessarily lead to a significantly greater number of bypass days because they naturally occur with low frequency in dry years. For example, loss of bypass flow days under the moderate and unregulated policies is similar for dry years (Table I), even though the volume of flow diverted to storage varied greatly between the two policies (Figure 6). In wet years, the strict and moderate policies had a relatively small effect on both bypass flow days and water security (Table I; Figure 6). The natural abundance of water in wet years means that diverters are consistently able to fill their reservoirs, even when restricted to periods when flows exceed the minimum bypass flow requirement.

DISCUSSION

Our results indicate that there are inherent tradeoffs between environmental flow protections and agricultural water security. Both environmental flow policies reduced the available supplies of water to vineyard agriculture, particularly in dry years. As expected, the most restrictive environmental flow policy, which effectively protected salmon bypass flows, was associated with the greatest impacts to agricultural water storage. However, the ecological benefit of the environmental flow policies (i.e. protection of bypass flow days) was not always proportional to their water security impacts. For example, the moderate policy actually offers less protection to bypass flow days than the unregulated scenario yet substantially restricted diversions for agricultural water storage. Thus, the environmental protection benefits of the moderate policy appear disproportionately small relative to the potential adverse effects on agricultural water users.

While the most significant zone of conflict between agricultural and environmental water needs might be expected to be in the lower watershed, where the cumulative effects of upstream water diversions are greatest, our findings indicate that the potential for conflict is greatest in small, upper watersheds. Because the flow threshold for fish bypass follows a negative exponential function with respect to catchment area [Equation (2)], while the magnitude of flows increases approximately linearly with catchment area, there is more water available and a significantly higher number of bypass days in large streams compared to smaller streams in the upper basin. As a consequence, the ecological sensitivity to water use impacts is greatest in small streams, where diversions can easily reduce the naturally limited period of salmon bypass flows. Agricultural water security for landowners in small watersheds is also most affected

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by the proposed environmental flow regulations. Protection of bypass flows substantially reduced the ability of water users in small watersheds to fill their reservoirs (Table III). These distinct patterns underscore the importance of spatially explicit modelling approaches for evaluating the benefits and costs of water management strategies (e.g. Willis and Whittlesey, 1998; Watanabe *et al*., 2006), particularly in decentralized management settings (Grantham *et al*., 2010).

Despite evidence that environmental flow regulations limited agricultural water diversions, in most water years, natural supplies were still adequate for meeting water storage needs regardless of policy restrictions. Furthermore, existing, permitted water users were generally unaffected by unpermitted water users and potentially new water users predicted by the econometric model. In the Maacama Creek watershed, the distribution of PODs across the landscape is such that most permitted water users are not located downstream of unpermitted diversions (Figure 1). Thus, the minimal effects of unpermitted on permitted users are probably not generalizable. In catchments with greater potential for vineyard expansion and increasing demands for water, the effects of new diversions could be significant.

The greatest effects of the policies and unpermitted users on agricultural water security were evident in dry years, when conflicts among water users and environmental needs are often severe (Gasith and Resh, 1999; Ward and Booker, 2003). This suggests that the development of sustainable water management policies should focus on drought scenarios, when reconciling competing demands is most challenging. Drought-year management is particularly important for threatened salmonids in coastal California, where lower flows in streams have been shown to increase the risk of mortality (Grantham *et al*., 2012). Furthermore, widespread population declines and loss in genetic diversity have made California's salmon taxa particularly vulnerable to environmental perturbation (Carlson and Satterthwaite, 2011; Katz *et al*., 2012). Thus, effective environmental flow management during drought periods is probably critical for the conservation of California's salmon species.

Nevertheless, some have argued that environmental flow allocations are unlikely to be sufficient for conserving river ecosystems in light of increasing demands for human consumptive uses. According to Pittock and Lankford (2010), demand management measures are essential for reducing consumptive needs and optimizing freshwater biodiversity conservation. In coastal California, vineyard agricultural generally relies on drip irrigation and thus already has relatively efficient water use compared to other crops. Furthermore, because water projects in the region are private and distributed across the landscape often with steep terrain, there is limited potential for infrastructure that would allow for water transfers to improve efficiency (Hanak *et al*., 2011). Water re-use is a promising solution for improving efficiency in coastal California (Bischel *et al*., 2011), although the potential to recycle urban wastewater for agricultural uses is subject to similar infrastructure constraints as water transfers. Improved coordination of water management probably has the greatest potential for reducing pressures on river ecosystems in coastal California. Because water users can control the timing of water withdrawals, coordination among upstream and downstream water users to de-synchronize diversions could improve local supplies and likely offset cumulative impacts.

The evaluation of tradeoffs between human and environmental water uses is often constrained by spatial incompatibilities between socio-economic and biophysical data (de Lange *et al*., 2010; Newburn *et al*., 2011). In the study, we reconciled this issue by considering parcel-scale property ownership and individual water rights, which are known to influence water use and allocation strategies (e.g. Loomis, 1998; Green and O'Connor, 2001; Briand *et al*., 2008). Furthermore, we examine the impacts of water use by measuring the loss of salmon bypass flow days, which has greater ecological relevance than hydrological impact metrics such as the volume or degree of flow reduction. By integrating local water use behaviour with the GIS-based hydrologic model, the consequences of environmental flow policies on ecologically relevant flows and water security could be assessed. We attempted to provide realistic model simulations, accounting for the spatial and temporal complexity of water availability, human demands, and environmental flow policies. However, further work is needed to validate assumptions and refine modelling of water user behaviour and ecological flow thresholds. Additional study of streams in upper watersheds is particularly needed, given that they are rarely monitored yet have been identified as significant zones of conflict from a water management perspective.

This type of analysis supports the development and evaluation of environmental flow standards and can be integrated with broader frameworks for sustainable water management, which emphasize the need for multi-disciplinary collaboration (Baron *et al*., 2002; Poff *et al*., 2003; Richter *et al*., 2006) and holistic approaches (Postel, 2002; King and Brown, 2006). For example, Richter *et al*. (2003) define a six-step process for developing an ecologically sustainable water management programme, which involves estimating key ecosystem flow requirements, accounting for human influences on the flow regime, identifying incompatibilities between human and ecosystem needs, collaboratively searching for solutions, conducting water management experiments, and, finally, developing and implementing an adaptive water management plan. The approach presented here directly facilitates the first three steps by (i) predicting an important ecological flow threshold across the stream network, (ii) assessing the hydrologic effects of human water use, and (iii) quantifying the tradeoffs between human and ecosystem needs with a focus on temporal and spatial dimensions. The ultimate effectiveness of any management approach in balancing human and ecosystem needs hinges on the fourth step: the collaborative search for solutions and reconciliation of competing interests, which remains a major challenge in California (Hanak *et al*., 2011) and other water-stressed regions of the world. Such negotiations will require society to make value judgments over the socio-economic benefits of consumptive water uses versus the benefits of maintaining healthy ecosystems. Analyses such as these will become increasingly important for accurately quantifying tradeoffs and informing such decisions.

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