

Systematic Screening of Dams for Environmental Flow Assessment and Implementation

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Environmental flow protections are crucial to the conservation of freshwater biodiversity in dam-regulated river systems. Nevertheless, the implementation of environmental flows has lagged far behind the pace of river ecosystem alteration. The vast number of dams now in operation and the substantial resources required to modify their operations suggest that a systematic approach is needed to identify rivers potentially benefiting from environmental flows. Here, we develop and apply a screening framework that is focused on the selection of dams that warrant environmental flows on the basis of evidence of hydrologic alteration and ecological impairment. Our approach is illustrated for California, where 181 (of an initial 1400+) dams are identified as high-priority candidates to improve environmental flows for native fish conservation. Given the rapid declines of freshwater biodiversity and pervasive alteration to rivers, this systematic screening approach should be useful for guiding the strategic implementation of environmental flows.

Keywords: rivers, water management, environmental flows, fish conservation, California

The proliferation of dams since the mid-twentieth century has altered river ecosystems at a global scale. Currently, there are an estimated 50,000 large dams (more than 15 meters [m] high) in operation and millions of smaller impoundments throughout the world (Berga et al. 2006, Lehner et al. 2011). Furthermore, energy and water scarcity challenges associated with climate change and human population growth continue to fuel the demand for large water projects (Palmer et al. 2008), which suggests that the number and extent of dams will continue to grow. The important societal benefits of dams, such as flood control, water supply, and hydropower, have also come with substantial environmental costs (WCD 2000, Bruno and Siviglia 2012). Dams are a dominant driver of global freshwater biodiversity declines (Dudgeon et al. 2006), fish species extinctions (Xenopoulos et al. 2005, Reidy Liermann et al. 2012), and river floodplain degradation (Opperman et al. 2010). Therefore, there is mounting pressure on policymakers and resource managers to realize the potential benefit of water infrastructure development while ensuring the long-term sustainability of freshwater ecosystems.

The modification of dam operations to control the timing and magnitude of flow releases for environmental benefits (i.e., environmental flows) has been proposed as an approach for mitigating the negative ecological impacts of dams while preserving essential water management

functions (Richter and Thomas 2007, Pittock and Hartmann 2011, Arthington 2012). By manipulating the quantity, timing, and quality of water releases from reservoirs to mimic natural flow dynamics, it may be possible to restore essential ecosystem processes on which aquatic organisms depend (Poff et al. 1997). Although the structural design and operational purposes of dams necessarily limit the potential to restore natural flow regimes, re-operating dams for environmental flows is becoming an increasingly important strategy for freshwater ecosystem conservation in regulated rivers (Konrad et al. 2012).

A wide range of approaches has been developed to support quantification and implementation of environmental flows (Tharme 2003, Williams 2011). Poff and colleagues' (2010) ecological limits of hydrologic alteration approach (ELOHA) represents the latest effort to develop a science-based environmental flow assessment framework. The approach establishes environmental flow standards at the regional scale by defining river classes that exhibit similar hydroecological conditions and expected responses to flow regime change. By developing standards at the regional scale, ELOHA is intended to improve the cost efficiency of environmental flow assessments, which have traditionally been conducted at river- or project-specific scales. The ELOHA framework has been adopted in distinct geographic regions, including river basins in the United States, Spain, China, Australia,

and South America (Pahl-Wostl et al. 2013). However, the significant financial and technical resources generally required to apply ELOHA have hindered its implementation in other jurisdictions (Richter et al. 2012), which suggests that environmental flows will continue to be implemented opportunistically in river basins where resources and political and institutional capacities are greatest (e.g., Moyle et al. 1998, Richter et al. 2006).

Environmental flow protections remain limited or nonexistent in the vast majority of the world's regulated rivers, and resource constraints make it unlikely that ELOHA (and other environmental flow assessment frameworks) will be comprehensively applied in the near future (Richter et al. 2012). Although opportunistic implementation of environmental flows will remain important, such as through dam relicensing procedures (Pitcock and Hartmann 2011, Williams 2011) and various state programs (Gillilan and Brown 1997), a broader strategy to improve environmental flows in regulated river systems is needed. Here we propose a systematic, data-driven approach to screen and select dams that may require managed environmental flows to sustain freshwater biodiversity based on indicators of hydrological and ecological impairment. The approach allows for a preliminary evaluation of environmental flow management needs over broad spatial scales by compiling and analyzing data relevant to the ecological and hydrologic impacts of individual dams. The purpose of the approach is to guide strategic investment in environmental flow investigations for river basins where environmental flows are needed most, which complements assessment frameworks such as ELOHA that are designed to establish specific flow standards once a system of interest has been identified. The approach is intended for agencies, non-governmental organizations, and policymakers that must consider how to prioritize the rivers on which they work and in which they invest resources.

We illustrate the approach for the state of California, which covers approximately 425,000 square kilometers [km²] and contains more than 1400 large dams (defined by the state as more than 1.8 m high and storing more than 60,000 cubic meters [m³]) and tens of thousands of smaller impoundments. Many of these dams are operated with little consideration for their effects on aquatic ecosystems and are a dominant factor responsible for the rapid decline of the state's native fish fauna (Moyle 2002, Moyle et al. 2011). In California, some dams are required to release environmental flows for salmon and other fish listed under the federal Endangered Species Act (ESA). In addition, hydro-power dams regulated by the Federal Energy Regulatory Commission (FERC) increasingly require environmental flow releases to mitigate their impacts on fish and other downstream biota (Viers 2011). However, most dams in the state are not subject to federal ESA or FERC requirements. State law (California Fish and Game Code §5937) does mandate that dam operators release sufficient water to support fish downstream. Furthermore, recent successful lawsuits have indicated that the Fish and Game Code

may become an increasingly important policy mechanism for securing environmental flows below dams (Gillilan and Brown 1997, Börk et al. 2012). However, determining which dams may not be in compliance with the code is a daunting task that state agencies have not undertaken to date. To help guide future implementation of environmental flow programs in California, we developed and applied the screening framework to identify dams for which environmental flows may be warranted. Here, screening criteria are focused on indicators of hydrological alteration and fish population impairment, but the framework can be adapted for application in other regions, especially where protection of public trust resources, such as rivers and streams, are required by law (Gillilan and Brown 1997, Viers and Rheinheimer 2011).

Screening dams for environmental flow management in California

The screening framework provides a data-driven process to identify and rank dams for which environmental flow protections appear warranted. Its application is intended for broad geographic regions, which are characterized by high biogeographic diversity and a widespread distribution of dams. The framework consists of a series of tiered filters that are used to screen dams on the basis of their physical and geographic attributes, hydrologic impacts, and potential ecological effects (figure 1). First, dams that meet minimum size and catchment area specifications are identified. Next, the hydrologic conditions below these dams are assessed to quantify the extent to which flows may deviate from natural, unimpaired conditions. Third, the potential impacts of dam operations on the biotic community in proximity to each dam are evaluated. Finally, the dams that satisfy all filters are identified and ranked by multiple criteria. The selected subset of ranked dams provides the basis for strategically pursuing site-specific assessments of dam operations and environmental flow requirements.

Characterizing physical and geographic attributes. To develop a dam database for California, records were compiled from several existing data sets, including the US Army Corps of Engineers National Inventory of Dams (USACE 2010), California Department of Water Resources List of Jurisdictional Dams (DWR 2010), and National Marine Fisheries Service's Dam Dataset for Assessing Anadromous Fish Passage (Goslin 2005). The data sets include most large dams in California, which are defined as being at least 1.8 m high with a storage capacity of more than 60,000 m³ (or more than 7.6 m high and storing at least 18,500 m³). Individual dams were mapped in a GIS format (ArcGIS version 10.1; ESRI, Redlands, California) by their latitudinal and longitudinal coordinates and, where necessary, manually geolocated on the basis of the 1:100,000 National Hydrography Dataset streamline layer and orthorectified aerial photos.

We first filtered dams for their potential to be managed for environmental flows by excluding dams that create off-stream storage, such as hydropower facilities (e.g., penstocks

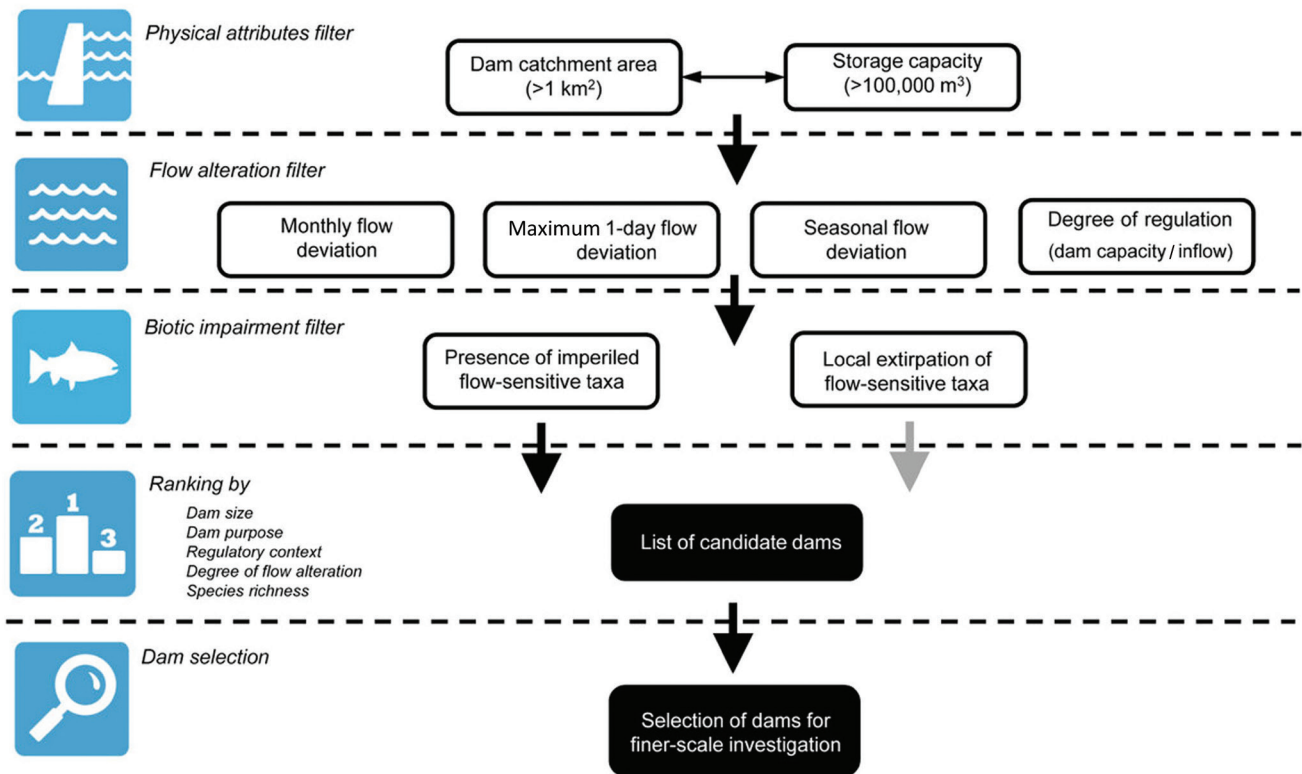


Figure 1. Screening framework for dams at which environmental flow management may be warranted on the basis of physical dam attributes and indicators of flow alteration and biotic impairment. The candidate dams are ranked on the basis of physical characteristics, regulatory context, and ecological values to prioritize sites or river basins for environmental flow assessment. Abbreviations: km², square kilometers; m³, cubic meters.

and forebays) and projects in highly urbanized catchments (e.g., wastewater treatment facilities and off-stream percolation basins). Debris basins, retention ponds, and similar passive impoundments were also excluded. For dams that consisted of multiple project works (e.g., those with multiple dikes and spillways), we included only the primary impoundment structure. Finally, dams with drainage areas less than 1 km² and with storage capacities of less than 100,000 m³ were excluded. Although small impoundments also impair stream flows (Smith et al. 2002) and can have significant ecological effects (Gangloff 2013), they were excluded because of their limited potential to be managed for environmental flows relative to that of larger dams.

Assessing hydrologic alteration. The second filter considers the effects of dams on downstream flows. A common approach to quantifying the hydrologic impacts of dams involves a comparison of observed (altered) downstream flows with expected (unimpaired or baseline) conditions. Expected hydrologic conditions can be estimated by modeling techniques, including process-based watershed models (e.g., Singh and Woolhiser 2002, Kennen et al. 2008) and statistical approaches (e.g., Sanborn and Bledsoe 2006, Carlisle et al. 2010a) or can be derived empirically from pre-dam

data (e.g., Batalla et al. 2004). Observed conditions are then compared with predictions of expected unimpaired flows to assess hydrologic alteration for indices describing different aspects of flow regime, such as the ratio of observed to expected monthly discharge (O:E; Carlisle et al. 2010b). When empirical flow data are unavailable, an alternative metric for assessing hydrologic alteration is the ratio of the reservoir storage capacity to the mean annual inflow—here referred to as the *degree of regulation* (DOR; Hirsch et al. 1990, Lehner et al. 2011). The DOR reflects the capacity of a dam to capture the annual discharge volume of a river and has been shown to be strongly correlated with other hydrologic alteration metrics, such as reductions in peak-flow magnitudes and a disruption of seasonal flow patterns (Batalla et al. 2004, Kondolf and Batalla 2005).

To evaluate hydrologic alteration below dams in California, we first identified the dams with downstream US Geological Survey (USGS) flow gages. The analysis was restricted to gages located below dams with limited or no tributary influence and with at least 10 years of continuous daily flow records between 1970 and 2012. Dams in close proximity to each other (e.g., storage dams with downstream hydropower facilities) were associated with the same downstream gage. At all gages we assessed potential changes in the magnitude

and seasonality of monthly flows and changes in the magnitude of maximum 1-day flows. Predictions of expected, unimpaired monthly, and maximum 1-day flows were generated using a statistical modeling approach developed by the USGS (Carlisle et al. 2010a, 2010b). Random forest models (Breiman 2001) were used to parameterize the relationships between geospatial catchment attributes (e.g., climate, topography, soils) and hydrologic responses at reference gages (i.e., those with no upstream dams and limited land-use disturbance) and then to predict hydrologic conditions at other locations on the basis of upstream catchment characteristics (see appendix S1 for more information). Catchment variables for the reference gages and those identified below dams were obtained from the Gages-II database (Falcone et al. 2012). Modeled predictions of unimpaired monthly and maximum 1-day flows were compared with observed values at the gages below dams to generate O:E ratios of the flow metrics. Alteration of seasonal flow patterns was also assessed by quantifying the correlation (Pearson's r) between observed and expected mean monthly flows.

Because of the limited geographic distribution of USGS gage stations, information on downstream flows was not available for the majority of dams evaluated in this study. However, the potential for flow alteration was assessed for all dams by the DOR. Volumetric storage capacity was derived from the dam datasets. The mean annual inflow was estimated from 61 years (1950–2010) of predicted unimpaired annual surface flows at each dam location using the statistical modeling approach described above (and in appendix S1). To consider the potential influence of upstream dams, cumulative DOR was also calculated: for each dam, the reservoir capacity was added to the capacity of all reservoirs in the dam's upstream catchment, and the total was divided by the mean annual inflow.

Assessing biological conditions. The third tier of the evaluation framework assesses the potential impacts of dams on the aquatic ecosystem. For the assessment of dams in California, ecological criteria were focused on native fish taxa because of their management relevance and because fish are strong indicators of river ecosystem condition (Esselman et al. 2013). Furthermore, extensive knowledge of the population status, distribution, and life history requirements of California's fish fauna has been gained from previous studies and environmental monitoring (Moyle 2002, Moyle et al. 2011). Although other taxonomic groups, such as benthic macroinvertebrates, are known to be sensitive to flow alteration (Konrad et al. 2008, Carlisle et al. 2010b), uniform statewide data were not available to allow for consistent comparisons among dams and were therefore not included as ecological screening criteria.

To identify dams that had the potential to affect native fish species of management concern, we selected a set of 67 species known to be vulnerable to dam and diversion impacts based on their distribution, documented impacts of flow alteration, and their life history requirements (Marchetti

and Moyle 2001, Brown and Ford 2002, Moyle 2002, Moyle et al. 2011). The group represents approximately half of California's 133 native fish taxa and includes wide-ranging migratory species, such as salmon, steelhead, lamprey, and sturgeon, in addition to other native riverine fishes threatened by dams and diversions (appendix S2). The excluded species were those that occur in lentic habitats or in isolated spring systems and riverine species resilient to hydrologic alteration. We further restricted the focal group to 42 species considered endangered or vulnerable to extinction on the basis of a recent population status assessment (appendix S2; Moyle et al. 2011). The current ranges of all focal species were mapped at the Hydrologic Unit Code 12 (HUC12) watershed scale (NRCS and USGS 2014), using methods described in Santos et al. 2014.

Biological screening criteria (figure 1) were applied to identify the dams located in watersheds in which imperiled, flow-sensitive species were potentially present. The screening approach was therefore focused on dams that had the potential to affect species of management of concern, which would presumably benefit from environmental flows. Dams located in watersheds with no imperiled flow-sensitive fish species were excluded because they are likely to be low-priority candidates for environmental flow management. A second screening criterion was applied to identify watersheds with dams in which imperiled flow-sensitive species had been lost. Local extirpations were assessed by comparing historic and current range maps for California native fish species (Santos et al. 2014). Environmental flow releases below dams where species have been extirpated may not provide immediate ecological benefits but may be important for the long-term recovery of imperiled species. We did not consider the full range of factors, including invasive species, habitat modification, and water quality degradation, that influence the population status and range of the fishes in the affected watersheds. Therefore, the ecological screening criteria provide evidence that dams may warrant environmental flows to protect imperiled fish species but do not address the feasibility or potential ecological benefits of dam reoperation, which may be limited by other physical, biological, and social factors.

The screening and ranking of candidate dams. The tiered screening framework was applied to identify the subset of dams with evidence of both hydrologic alteration and fish impairment. The criteria for hydrologic alteration were deviation from observed flow patterns (the magnitude of monthly and maximum 1-day flows and seasonality) and high values for DOR and cumulative DOR. Although there are no generalizable ecological-flow relationships that can be used to set objective ecological sustainability thresholds for flow impairment (Poff and Zimmerman 2010), a review of environmental flow standards suggested that flow alteration greater than 20% is likely to cause moderate to major changes in ecosystem structure and functions (Richter et al. 2012). We considered deviation in monthly and maximum 1-day flows of 50% as a reasonable

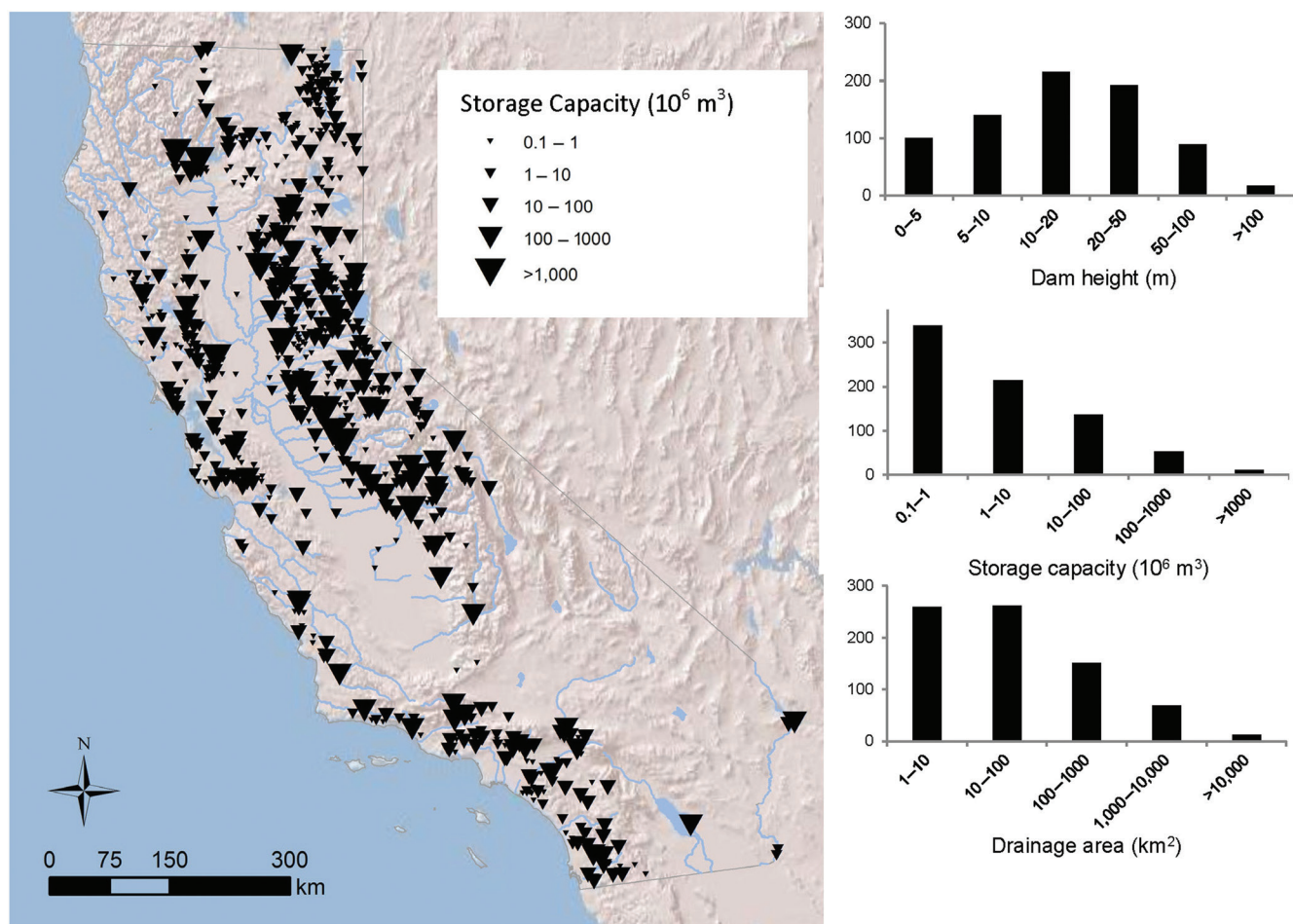


Figure 2. Distribution of the dams evaluated ($n = 753$), with frequency distributions for dam height, storage capacity, and catchment area. Abbreviations: km, kilometers; km^2 , square kilometers; m, meters; m^3 , cubic meters.

threshold criterion at which adverse ecological effects may occur, and this is large enough to limit the potential effects of model uncertainty on flow alteration predictions (i.e., O:E flow metrics; appendix S1). The threshold criterion for deviation in seasonal flow patterns was defined by a correlation coefficient (Pearson's r) of less than 0.5. Finally, we used a DOR or cumulative DOR index greater than 1 as a criterion for hydrologic alteration, on the basis of previous studies that have shown DOR approaching or exceeding 1 to be a strong indicator of flow regime impacts (Batalla et al. 2004, Eng et al. 2012). Biological impairment criteria were satisfied by the presence or local extirpation of any flow-sensitive fish species with an imperiled population status (i.e., *endangered* or *near-threatened* per Moyle et al. 2011). Dams satisfying one or more hydrologic criteria and associated with indicators of fish impairment were included in a final subset of dams (figure 1).

The dams identified through the screening process were sorted and ranked on the basis of their size (height and reservoir capacity) and the hydrologic alteration criteria. These sorting criteria emphasize the largest dams and those with the greatest potential for significant flow regime impacts. Additional sorting criteria were applied to identify the dams

affecting rivers of potential significance for fish conservation, such as the number of imperiled flow-sensitive fish species and the total richness of native fish species present in the affected watershed. Candidate dams were also distinguished by their primary purpose, designated in the US National Inventory of Dams (USACE 2010). Finally, dams subject to federal ESA and FERC requirements were distinguished from dams primarily managed under state jurisdiction.

Mapping California's dams

A total of 1440 unique California dam records were compiled from existing data sets (Goslin 2005, DWR 2010, USACE 2010). From this list, 515 were identified as off-stream dams, retention basins, or other facilities that do not release water directly into streams. An additional 172 dams with small drainage areas (less than 1 km^2) or low storage capacities (less than $100,000 \text{ m}^3$) were excluded. The 753 remaining dams were selected for further assessment. These dams represent a broad range of sizes, storage capacities, and drainage areas (figure 2) and include those that are privately owned ($n = 339$) and those owned and operated by local ($n = 279$), state ($n = 27$), and federal agencies ($n = 108$). The

dams are also managed for a range of operational purposes. According to the purpose designations in USACE (2010), the evaluated dams are primarily operated for irrigation ($n = 328$), hydroelectric production ($n = 133$), and water supply ($n = 133$). However, nearly all dams were reported as having multiple operational purposes, and the relative importance of each operation type is not specified in USACE (2010).

Flow regime alteration below dams

A total of 211 USGS flow gages were identified downstream of 228 dams. The potential alteration of flow magnitudes and seasonal flow patterns at those gages was first assessed by comparing modeled unimpaired monthly flows with the observed flows. The observed monthly flows were calculated from daily flows at gages with at least 27 observations per month for water years in the period of record, resulting in a set of 205 gages below 224 dams. Expected monthly flows from 1950 to 2010 were estimated at all gages from the unimpaired flow models, which performed well in predicting flows at reference gages excluded from the model training data set (appendix S1). Mean monthly O:E ratios were calculated at each gage from the set of paired observation–model values within the period of record.

Nearly all of the gaged dams showed evidence of monthly flow alteration. Of the 224 dams evaluated, 202 had at least 1 month in which the observed monthly flows deviated from expected values by greater than 50%. For 26 dams, monthly flows were altered by greater than 50% for all 12 months and, for most dams ($n = 183$), monthly flows were altered by greater than 50% for 6 months or more. Mean monthly O:E values were less than 1 for most dams in the winter and spring, which indicates that flow releases from most dams were, on average, lower than expected surface flows (figure 3a). However, in the summer and fall, many of the dams had monthly O:E values greater than 2, which may represent augmented flow releases in late summer for agricultural water deliveries.

The change in seasonal flow patterns was assessed by examining the correlation between paired observed and expected monthly flows at each gage (figure 3b). At most of the dam gages ($n = 87$ of 213), the observed and expected monthly flows were strongly correlated ($r > 0.75$), which indicates that monthly seasonal flow patterns were generally preserved. However, low correlations ($r < 0.5$) of monthly flows at 46 gages indicated that seasonal flow patterns were highly altered in those rivers (figure 3b). Negative correlation coefficient values were observed at four gages, which indicates a reversal of natural seasonal flow patterns.

Next, the potential effects of dams on downstream peak flows were assessed by comparing observed with expected values of the mean maximum 1-day flow. Only gages with more than 350 days of daily flow records per year for 10 years were included ($n = 209$). Mean O:E values were calculated at each site for the period of record by comparing observed values with modeled predictions of maximum

1-day flows for all water years with records between 1950 and 2010. The model performed well in predicting the maximum 1-day flows at validation sites omitted from model training (appendix S1), which indicates that significant deviation (greater than 0.5) in O:E from 1 is attributable to upstream dam operations and not model error. A high proportion of the gages ($n = 77$) exhibited relatively low deviation from expected maximum 1-day flows, with mean O:E values between 0.75 and 1.25 (figure 3c). At 45 gages, the maximum 1-day flows were less than 50% of the expected values, which indicates a reduction in peak-flow magnitudes, whereas a similar number of sites ($n = 53$) had observed maximum 1-day flow values that were greater than 50% of predicted values.

The degree of regulation was calculated for all of the dams ($n = 753$), including those without downstream USGS gages, by dividing the dam storage volume by the mean unimpaired annual inflow (the average of all annual predictions for water years between 1950 and 2010). The cumulative DOR was calculated as the total storage volume of the dam plus those of all dams in the upstream catchment divided by the mean annual inflow. The model-predicted unimpaired annual flows were estimated with high accuracy and low bias (appendix S1). Both DOR and cumulative DOR values for dams exhibited a bimodal distribution, with most dams having either values less than 0.25 (storage capacity less than 25% of annual inflow volume) or greater than 1 (storage capacity greater than mean annual inflow; figure 4). A total of 421 dams had a DOR greater than 0.5, 362 greater than 0.75, and 303 greater than 1. There were 180 dams with storage capacities greater than 2 times the estimated mean annual inflow ($\text{DOR} > 2$). Although the dams with high DOR values occur throughout the state, they are clustered in particularly high densities in arid regions, such as southern coastal California and the northeast part of the state (figure 4).

Indicators of fish taxa condition

To identify the dams that could adversely affect native fish populations, we screened for dams in watersheds occupied by imperiled fish species considered sensitive to flow alteration. Imperiled, flow-sensitive species primarily occurred along the California coast, within the Central Valley and Sierra Nevada foothills regions and in the Klamath River Basin in northern California (figure 5a). All of the dams within the range of imperiled flow-sensitive species (considered *endangered* or *near-threatened* per Moyle et al. 2011) were identified: 280 dams were within the range of at least 1 flow-sensitive species, including 269 within the range of resident (nonmigratory) species and 173 within the range of sensitive anadromous species.

A total of 421 dams were also identified in 315 HUC12 watersheds that have lost flow-sensitive species. The dams associated with species losses were concentrated in the southern California coast, the Sierra Nevada foothills, and

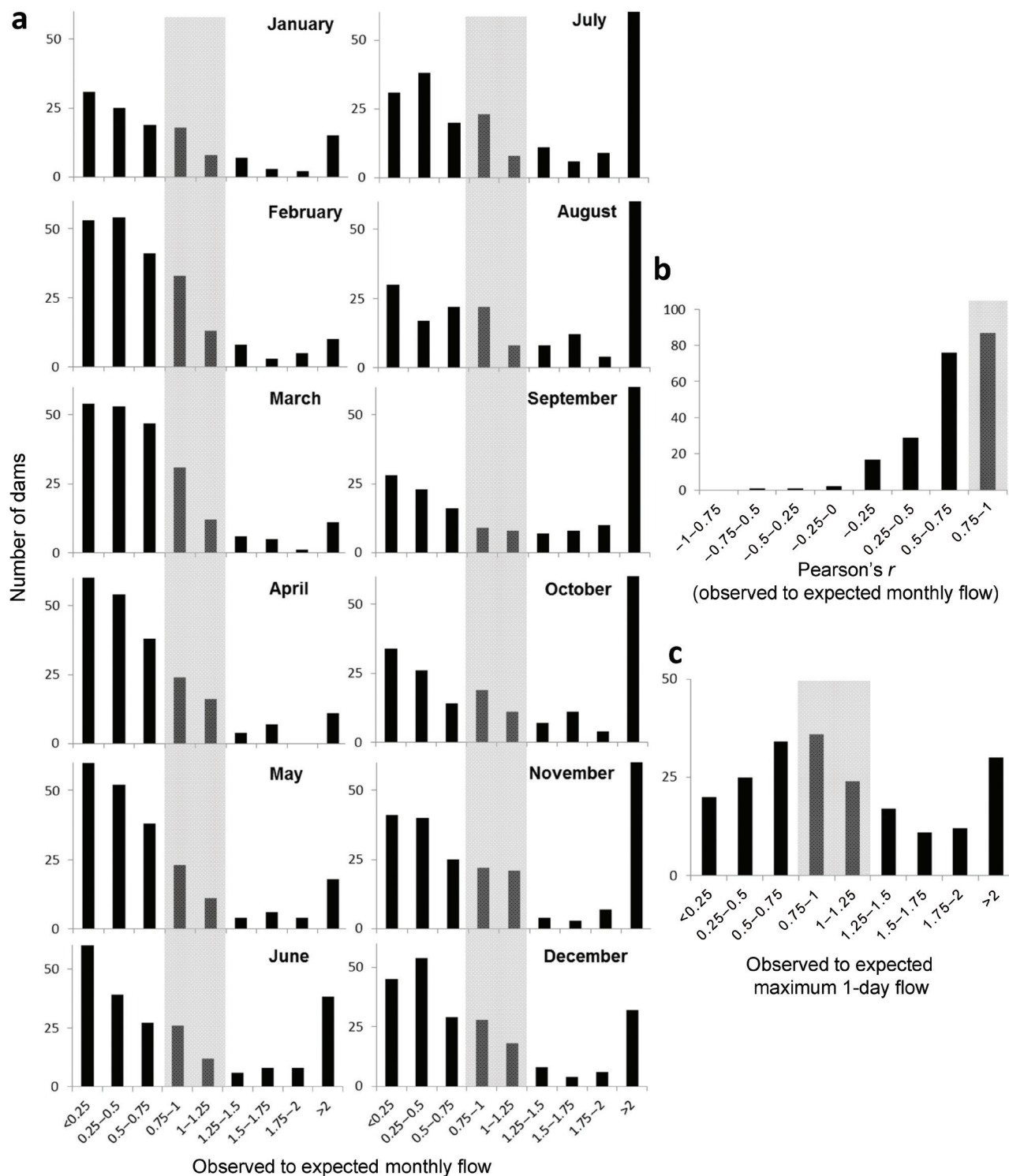


Figure 3. Histograms of (a) the ratio of observed to expected mean monthly flows, (b) seasonal flow deviation based on a correlation between the observed and expected monthly flows, and (c) the ratio of observed to expected 1-day maximum flow at gages ($n = 211$) below California dams. The gray shading indicates that the observed flows were similar to the expected (unimpaired) values.

the upper Sacramento and Klamath River basins (figure 5b). The losses were primarily attributed to range contractions of anadromous taxa from historic to present time: Steelhead trout were extirpated from 78 (HUC12) watersheds affected

by 107 dams, Chinook and coho salmon from 120 watersheds containing 162 dams, lamprey from 26 watersheds containing 26 dams, and sturgeon from 6 watersheds containing 10 dams.

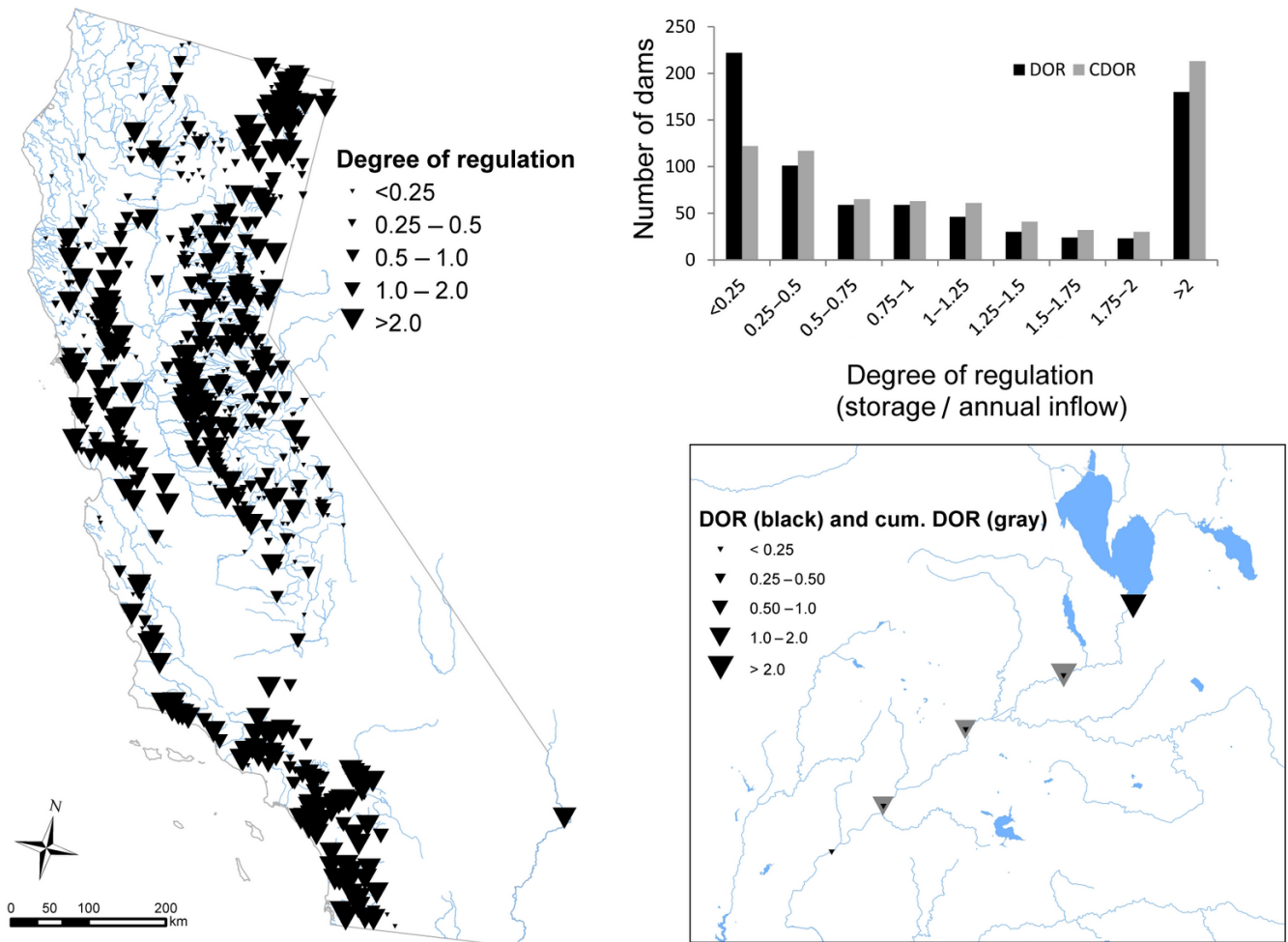


Figure 4. The degree of regulation (DOR) and cumulative DOR for dams in California, representing the local and cumulative reservoir storage capacity relative to the mean annual inflow. The inset map illustrates the difference between DOR and cumulative DOR for a series of dams on the North Fork Feather River. Abbreviation: km, kilometers.

Screening and ranking of candidate dams

Of the 753 dams evaluated, 460 were associated with at least one indicator of altered downstream flows. A total of 204 of the 224 gaged dams were associated with at least one indicator of flow alteration. There were 202 dams associated with modified monthly flows (a percentage deviation from the expected values greater than 50%) in at least 1 month, whereas 46 showed evidence of significant alteration to flow seasonality (a weak correlation between the observed and expected monthly flow patterns). There were also 89 dams associated with impaired maximum 1-day flows (a deviation greater than 50% from the expected values). A total of 377 dams had DOR or cumulative DOR values greater than 1.

Among the 753 dams, 280 were within the current range of imperiled, flow-sensitive fish species. Of these, 181 were also associated with at least one indicator of hydrologic alteration and are priority candidates for environmental flow assessment (figure 1, appendix S3). There were an additional 156 dams that occur in watersheds that have lost flow-sensitive

species (appendix S3). These dams also warrant attention for environmental flow management to potentially support the recovery of imperiled fish populations.

To further examine the final set of candidate dams associated with imperiled fish species and indicators of flow alteration, the dams were ranked and sorted by their physical features (reservoir capacity), hydrologic indicators (seasonal flow alteration and DOR), dam purpose, associated fish assemblage characteristics, and known regulatory requirements (appendix S4). The dams with large storage capacities were ranked because of their potentially significant influence on downstream water availability for fish. Most large storage dams are also designed to control the timing and magnitude of flow releases, which could facilitate the conjunctive management of reservoirs for multiple benefits, including flows for fish. The dams with the largest water storage capacities included Shasta Dam, on the Sacramento River; Don Pedro, on the Tuolumne River; and Monticello Dam, on Putah Creek.

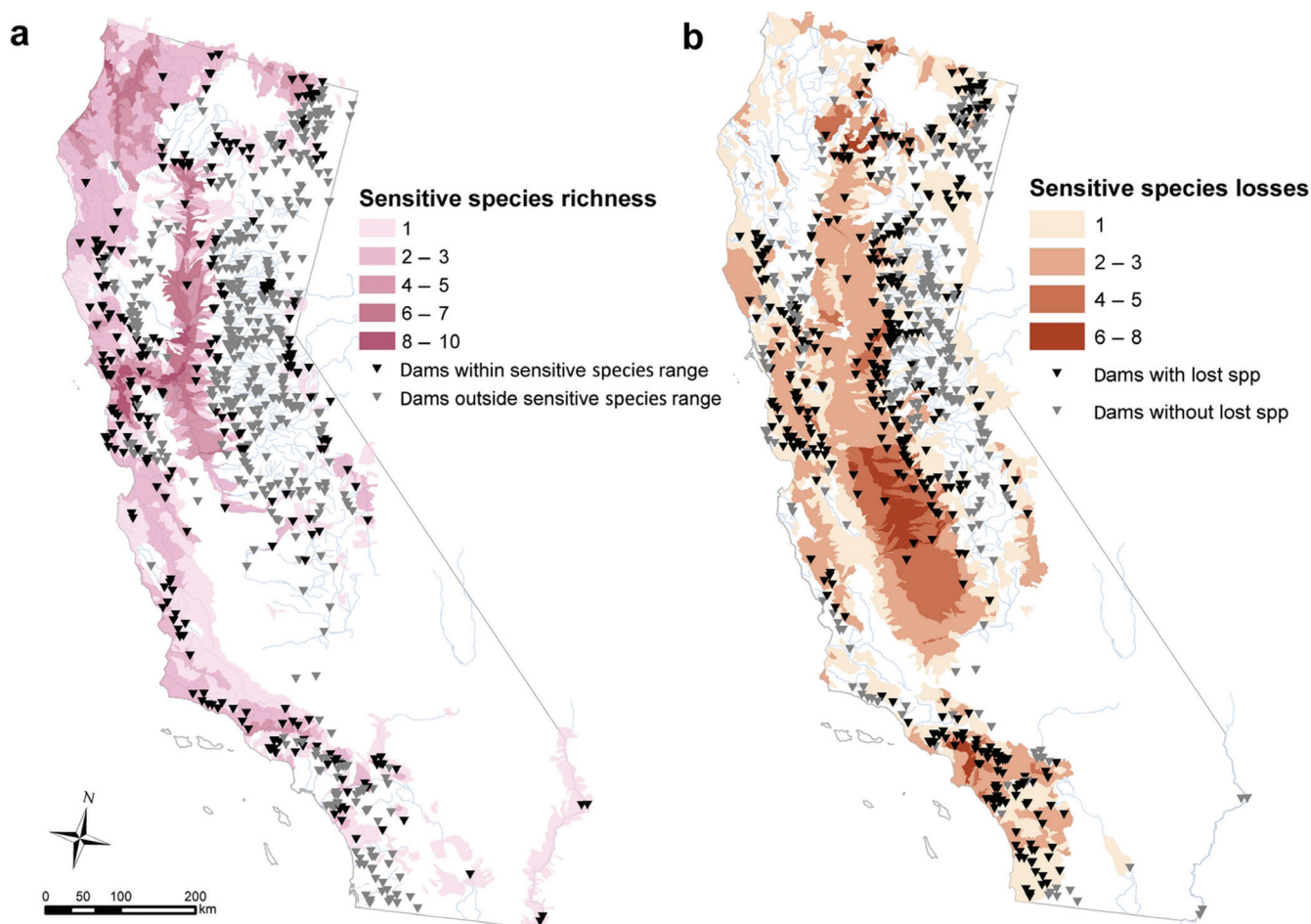


Figure 5. (a) Dams within the range of imperiled flow-sensitive species and (b) dams located in watersheds where flow-sensitive species have been locally extirpated.

Dams associated with the greatest downstream hydrologic alteration were also identified and ranked on the basis of their seasonal flow deviation (a correlation of O:E mean monthly flows) and DOR (capacity divided by the annual inflow; appendix S4). Many of the dams with high seasonal flow deviation were dams with relatively small storage capacities (less than $50 \times 10^6 \text{ m}^3$), such as Meadow Lake Dam (on a tributary of the north fork of the Mokelumne River; $r = -0.03$), Tinemaha Dam (on the Owens River; $r = 0.13$), and the Pit River No. 4 Diversion Dam (on the Pit River; $r = 0.36$). Similarly, the dams with the largest DOR values tended to have small storage capacities, which suggests that a dam's size is not necessarily indicative of its hydrologic effects.

The dams associated with a high number of flow-sensitive species and overall native fish species richness were also identified (appendix S4). Dams located in river basins with the highest number of imperiled flow-sensitive species included Camp Far West Storage and Diversion Dams (on the Bear River; six species), Red Bluff Diversion Dam (on the Sacramento River; six species), and Woodbridge Diversion Dam (on the Mokelumne River; five species).

These dams were also associated with the highest level of native species richness (15 or more native species). Other candidate dams located in watersheds with high native species richness were Lake Anza (on Wildcat Creek; 16 species), Whiskeytown Lake (on Clear Creek; 15 species), and several dams on the Sacramento River (Keswick, Shasta, and Anderson Cottonwood; 15 species each).

Finally, the dams' purpose and regulatory requirements were evaluated to consider the feasibility of, and appropriate policy mechanisms for, implementing environmental flows below the candidate dams. For example, 83 of the candidate dams had a primary designated purpose of irrigation, which may be more compatible with environmental flow management than dams whose primary purpose is water supply ($n = 45$) or hydropower ($n = 24$). Of the 181 candidate dams, 38 are subject to federal ESA or FERC regulations that require environmental flows (appendix S4). The remaining 143 dams with evidence of flow alteration and ecological impairment are therefore considered a high priority for assessing compliance with state environmental flow requirements.

Box 1. Restoring environmental flows in Putah Creek, California.

In the 1950s, the US Bureau of Reclamation built Monticello Dam, on Putah Creek, a tributary of the Sacramento River in Yolo County. Streamflow in lower Putah Creek is completely regulated, except when large storms cause the dam to spill over. During a late 1980s drought, releases were so low that a 30-kilometer section of lower Putah Creek dried, resulting in fish kills and harm to riparian wildlife. In response, a citizen's group; the University of California, Davis; and the city of Davis sued to increase flows (*Putah Creek Council v. Solano Irrigation District and Solano County Water Agency*). The trial court, citing California's Fish and Game Code §5937, ordered a 50% increase in the minimum release schedule to keep the creek flowing to its mouth. Subsequent negotiations led to the Putah Creek Accord, signed in May 2000, which established additional operational requirements to benefit fish and other aquatic organisms (Moyle et al. 1998).

The Accord's flow recommendations were based on the ecological needs of fish species and assemblages in the creek, assessed by expert opinion from long-term monitoring data, and included increased spring spawning and rearing flows for native fish, pulse flows to attract and support anadromous fish in the fall, and minimum flows to sustain fish in droughts. Nine years of creek monitoring indicate that the new flow regime has been successful in promoting the expansion and maintenance of native-dominated fish assemblages throughout the creek (Kiernan et al. 2012). Importantly, the restoration of native fishes was achieved by manipulating stream flows at biologically important times of the year and only required a small increase in the total volume of water delivered downstream (water that was not diverted) during most years.

In summary, we identified 181 dams for which improved environmental flow releases may be warranted on the basis of evidence of hydrologic alteration and fish population impairment. The assessment and implementation of environmental flows below an additional 156 dams may also be warranted to restore populations of flow-sensitive species that have been locally extirpated from watersheds in which the dams occur. The candidates for environmental flow management occur throughout the state and represent a broad diversity of ownership (e.g., public utilities, private, state agencies), impoundment sizes, and functions (e.g., flood control, water storage, diversions). Of the 181 priority dams, 38 are subject to FERC or federal ESA regulations that require environmental flows, although others may manage environmental flows in accordance with project-specific state and federal agency agreements. Although our analysis provides evidence of flow regime alteration and fish population impairment associated with all candidate dams, additional investigation is required to assess whether flow releases from dams are sufficient to maintain native fish populations and other desirable ecological features in downstream waters. In addition, an evaluation of other potential limiting factors (e.g., habitat degradation, nonnative species, pollution) not related to flows is necessary to determine whether environmental flow management is justified. Therefore, the ultimate determination of environmental flow needs (and compliance with state and federal environmental flow regulations) will require site-specific assessments, substantive social engagement, and possible legal enforcement (see box 1 for an example).

Conclusions

From an initial pool of 753 large dams in California, the screening process identified 181 candidate dams at which environmental flows may be warranted on the basis of

indicators of flow and ecological impairment. These dams fall within a broad range of biogeographic settings, sizes, and operational purposes. They all showed evidence of downstream flow alteration or had storage capacities that exceed annual inflows. For 65 of the 90 candidate dams with downstream flow gages, their observed monthly flows deviated from the expected values by 50% or more for at least 6 months of the year. Among the 181 candidate dams, 118 had storage capacities large enough to capture more than the average annual inflow. The candidate dams were also associated with indicators of fish population impairment; they were all located within the range of imperiled fish populations sensitive to flow alteration.

By identifying dams for which there is evidence of both flow alteration and ecological impairment, our screening framework provides a transparent and objective basis for determining where more time-consuming investments in environmental flow assessment are needed. This framework is intended for application over broad spatial scales for evaluating hundreds to thousands of dams, in which an initial screening is needed to prioritize effort and resources for agencies, nongovernmental organizations, and policymakers. It complements other environmental flow assessment approaches in which the specific ecological effects of dams are evaluated at the river basin scale (e.g., Risley et al. 2010).

Because of the large spatial scale at which the framework is applied, the screening criteria are restricted to relatively coarse indicators of ecological and hydrologic impairment that can be inferred from the best available region-wide data. Dams have the potential to affect freshwater ecosystems in a variety of ways that are not considered in this framework, including modifications to sediment transport processes (Vörösmarty et al. 2003, Schmidt and Wilcock 2008), thermal regime alterations (Olden and Naiman 2010), and facilitated nonnative species introductions (Moyle and

Mount 2007). These and other factors affecting habitat suitability and ecological responses to environmental flows must be evaluated through more detailed study. We reiterate that the framework is a screening-level tool that shows where environmental flows likely warrant attention, but decisions over where to invest resources in environmental flows for ecosystem restoration need to be supplemented by knowledge of local ecological, social, and economic conditions. The hydrologic and ecological screening criteria are focused on those dams for which environmental flows should be assessed but do not preclude the need for site-level investigations of the dams' impacts and the feasibility and potential benefits of environmental flows.

The lack of consistent information on dam operations, downstream flow regimes, and below-dam aquatic ecosystems is a significant barrier to environmental flow management and the sustainable use of water resources (Pahl-Wostl et al. 2013). The National Inventory of Dams (USACE 2010) offers the most comprehensive database of dams in the United States. The database characterizes general classes of use (e.g., water supply, hydropower) but contains no quantitative information on how dams are operated (e.g., the timing and volume of inflows, storage, and outflows). Although California has a relatively dense network of USGS stream gages, flow conditions below the vast majority of dams are unknown. Finally, assessing the ecological impacts of dams is constrained by limited and non-uniformly distributed biological observations (Santos et al. 2014). Given these knowledge gaps, there is a clear need to develop an integrated system of monitoring and reporting to better characterize the current state of aquatic ecosystems, hydrologic regimes, and anthropogenic modifications. Furthermore, such efforts must be closely linked to policy and governance processes to support effective implementation of environmental flow recommendations (Pahl-Wostl et al. 2013).

The degradation of freshwater ecosystems combined with escalating pressures on water resources requires strong management responses to conserve threatened freshwater biota and ecosystem services. However, the scale of ecosystem deterioration means that a systematic approach is needed to provide a strategic and scientifically defensible framework for implementing conservation measures (Nel et al. 2009, Linke et al. 2011). This is particularly true for securing environmental flow protections, which are often controversial and require substantial financial and technical resources for their implementation. Recent approaches to systematic freshwater conservation have been focused on protected area planning (Moilanen et al. 2008, Leathwick et al. 2010), systematic dam removal for improving fish passage (Kocovsky et al. 2009, Martin and Apse 2011, Null et al. 2014), and the prioritization of freshwater ecosystem restoration projects (Kauffman-Axelrod and Steinberg 2010). The proposed framework fills an important gap by supporting the strategic implementation of environmental flows.

In this study, the framework is focused on the selection of dams at which environmental flows may be important for conserving California's native fish populations. However, the screening approach can be adapted to other systems, screening criteria, and conservation targets. Furthermore, new ranking criteria can be used to support alternative conservation priorities, such as the protection of ESA-listed species or aquatic biodiversity hotspots. In some cases, state or federal regulatory requirements can also be used as criteria to prioritize dams for environmental flow assessments. For example, the screening results indicated that only 38 of the 181 candidate dams in California are regulated under federal FERC or ESA requirements, which indicates that state policy and enforcement mechanisms, such as Fish and Game Code §5937, may be necessary to assess and implement environmental flows in most of the state's priority dams.

Worldwide environmental flow programs (e.g., Bunn and Arthington 2002, Yarnell et al. 2010, Arthington 2012) show that re-operating dams to replicate ecologically meaningful aspects of the natural flow regime can help sustain riverine biota. Growing population pressures and climate change suggest that environmental flows will be an increasingly important strategy for freshwater ecosystem conservation. In California, for example, dams capable of storing and releasing cold-water flows will likely be crucial for sustaining salmon in river systems with warming climates (Null et al. 2010, Katz et al. 2012). Identifying dams located in river basins of conservation value could help set priorities for implementing environmental flows and other ecosystem restoration measures. Furthermore, projected changes in hydrology will also necessitate a reevaluation of dam safety, performance, and management policies (Pittock and Hartmann 2011, Viers 2011), which could present opportunities for operational or structural modifications (including dam removal). Therefore, understanding the relative importance of dams from an ecological perspective can help set management priorities and guide the strategic conservation of freshwater ecosystems.

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Supplemental material

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