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,

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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 (Pittock 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, nongovernmental 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 [km^2] 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 [m^3]) 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, hydropower 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 m^3 (or more than 7.6 m high and storing at least 18,500 m^3). 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

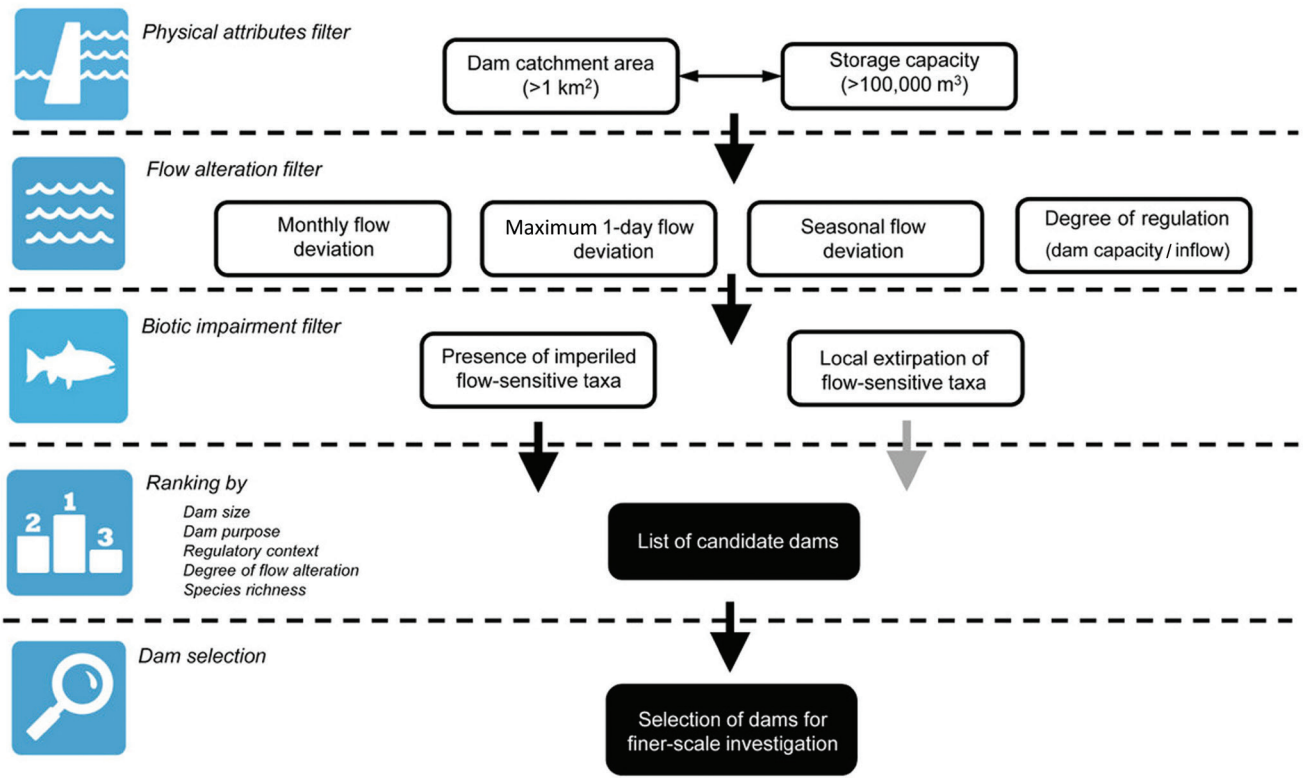

Figure 1. Screening framework for dams at which environmental flow management may be warranted on the basis of physical dam attributes and indicators of flow alteration and biotic impairment. The candidate dams are ranked on the basis of physical characteristics, regulatory context, and ecological values 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 km^2 and with storage capacities of less than 100,000 m^3 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 stugeon, 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 presumbably benefit from environmental flows. Dams located in watersheds with no imperiled flow-senstitve 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

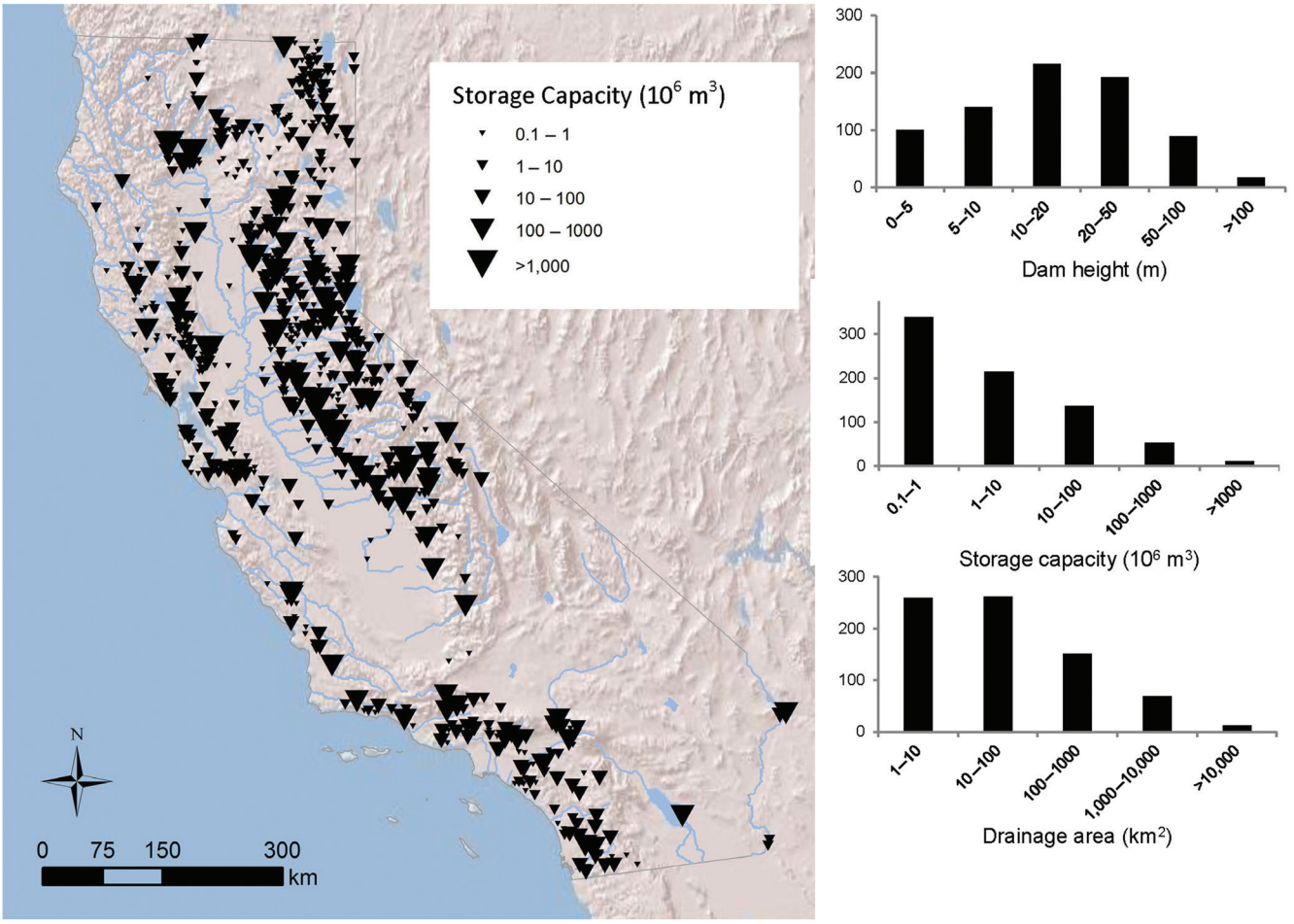

Figure 2. Distribution of the dams evaluated (n = 753), with frequency distributions for dam height, storage capacity, and catchment area. Abbreviations: km, kilometers; km^2, square kilometers; m, meters; m^3, cubic meters.

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 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 (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

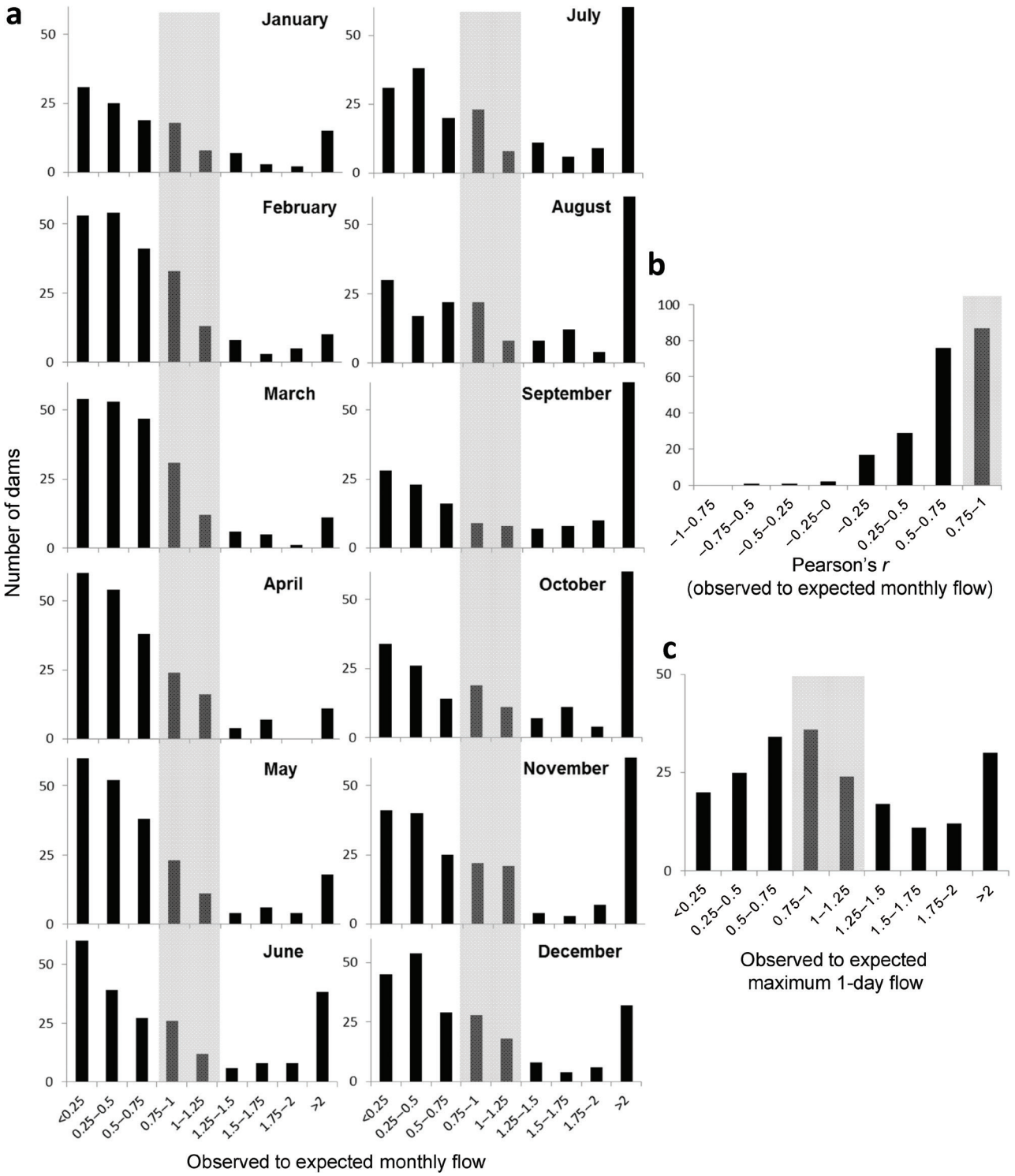

Figure 3. Histograms of (a) the ratio of observed to expected mean monthly flows, (b) seasonal flow deviation based on a correlation between the observed and expected monthly flows, and (c) the ratio of observed to expected 1-day maximum flow at gages (n = 211) below California dams. The gray shading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

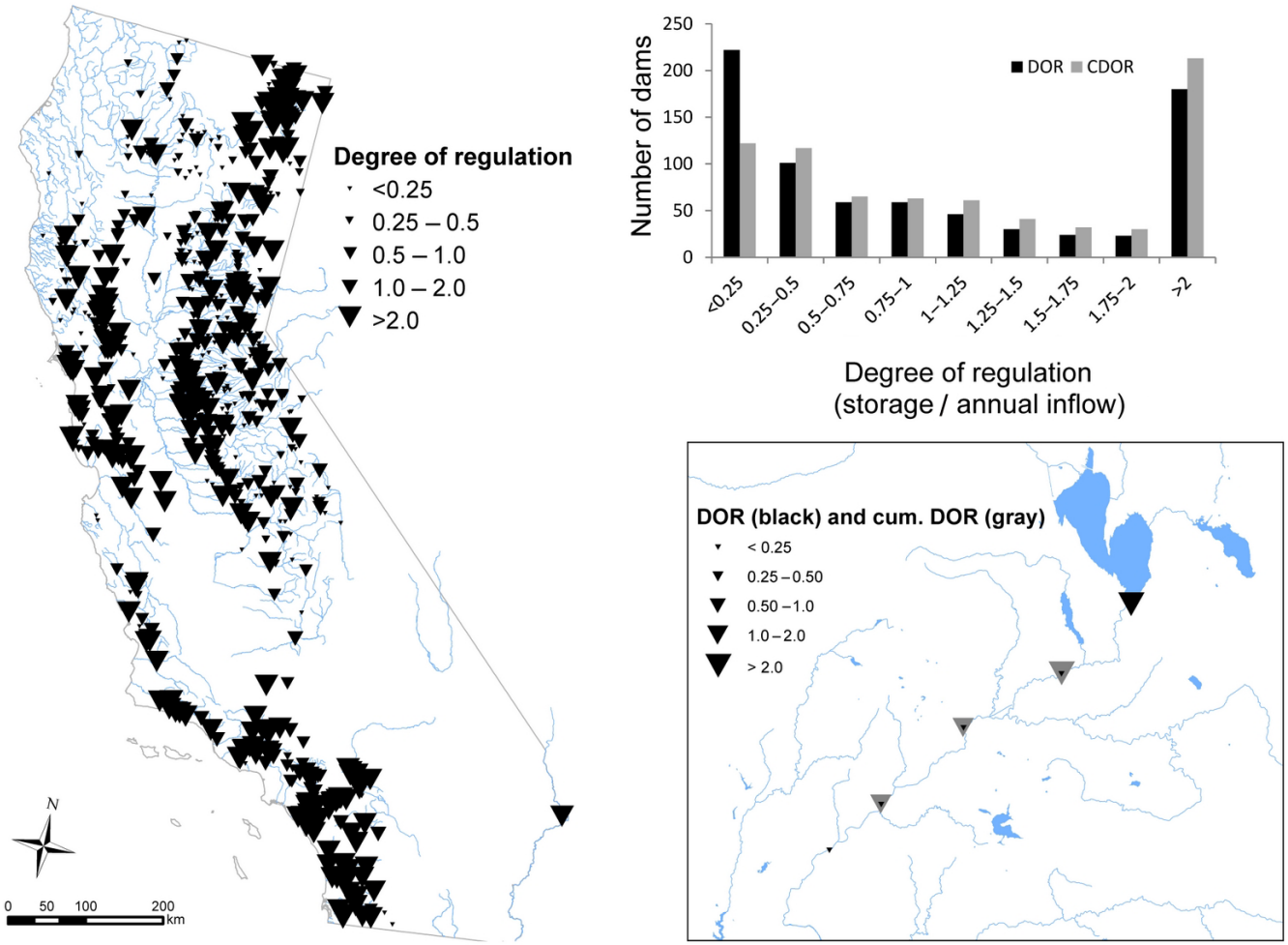

Figure 4. The degree of regulation (DOR) and cumulative DOR for dams in California, representing the local and cumulative reservoir storage capacity relative to the mean annual inflow. The inset map illustrates the difference between DOR and cumulative DOR for a series of dams on the North Fork Feather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

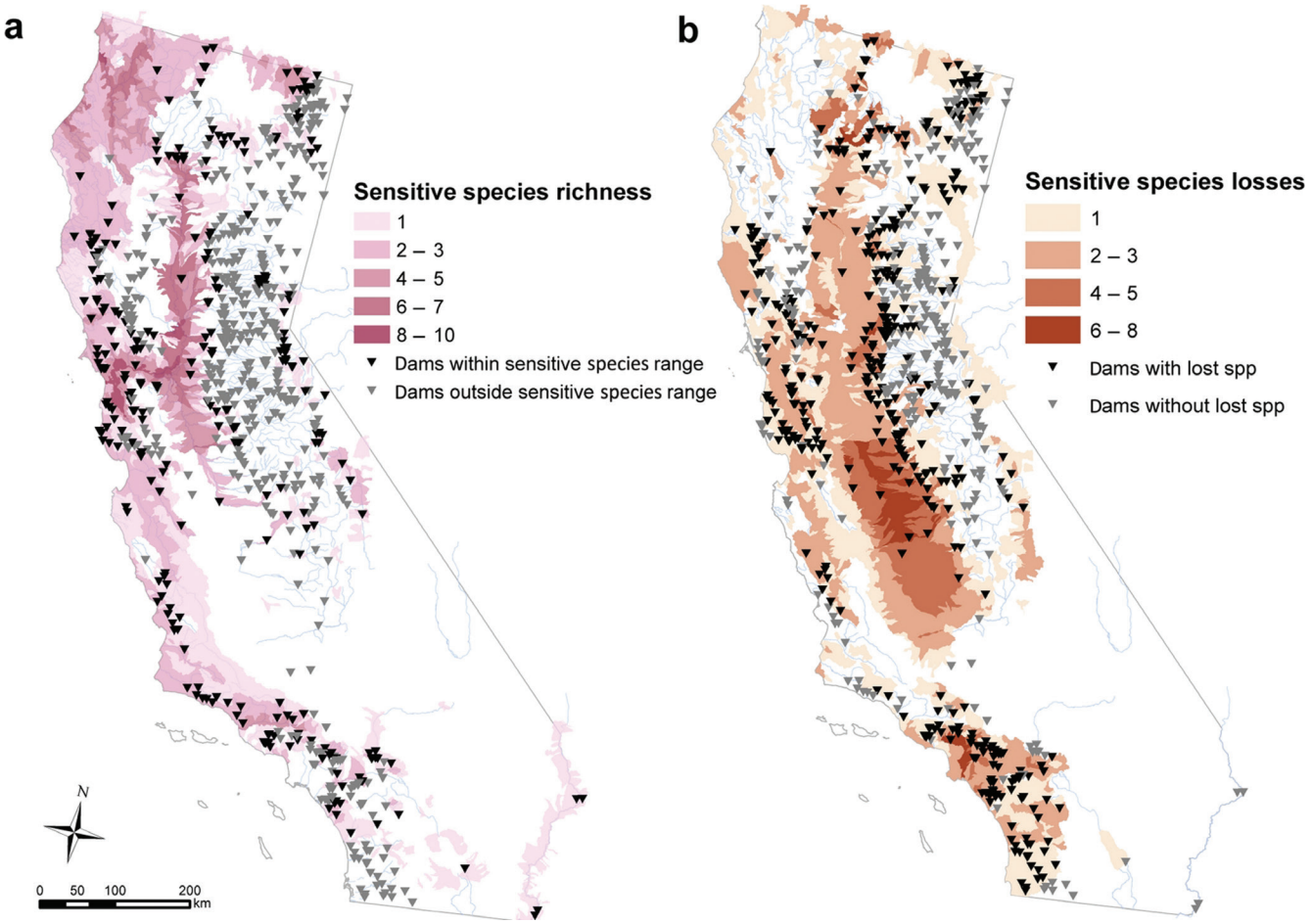

Figure 5. (a) Dams within the range of imperiled flow-sensitive species and (b) dams located in watersheds where flow-sensitive species have been locally extirpated.

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 50×10^6 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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Appendix S1. Hydrologic model description and performance evaluation

Hydrologic models were developed using Random Forests (RF) (Breiman 2001), a statistical modeling technique used for prediction and classification (e.g., Cutler et al. 2007). The RF modeling approach is described in detail in Carlisle et al. 2010 and applied here to predict expected, unimpaired flow metrics at select gage and dam locations. Briefly, RF are a model-averaging technique that produces thousands of regression trees, each with a bootstrapped sample of 70% of observations and a randomly selected subset of predictor variables considered at each branch. The remaining 30% of observations are withheld to evaluate model performance. RF models are implemented in R with the randomForest package (Liaw and Wiener 2002).

Separate RF models were developed to predict mean monthly, mean annual, and maximum 1-day flows. The models used data from 180 reference gages and 120 catchment predictor variables (e.g., climate, topography, soils and geology) in the Gages-II database (Falcone et al. 2011). Model predictions were compared with randomized subsets observed data withheld during RF model development to calculate several model performance metrics (Moriasi et al. 2007), including the coefficient of determination (r^2), Nash–Sutcliffe coefficient, and percent bias. In addition, predictive performance was assessed by sequentially excluding individual reference gages and re-running the models to evaluate observed against predicted (O/E) values at the omitted site. To improve predictive performance of the monthly and 1-day maximum flow models, separate models were developed for three subregions of California, which follow EPA Level-III ecoregion (Omernik 2007) boundaries and encompass the state's interior mountain, coastal mountain, and xeric regions. A single statewide model was used for predicting annual flow.

Flow alteration assessment at gages below dams. The models were used to predict unimpaired mean monthly and maximum 1-day flows at (non-reference) gages located below dams, based on the same set of catchment predictor variables used in model training. Observed values at the gage sites were obtained for each water year in the period of record between 1950 and 2010, and divided by model-predicted values from the respective water year. Mean O/E value for each metric was then calculated for each site over the period of record.

Model performance varied by region and by flow metric (Table S1.1-S1.3). The monthly and 1-day maximum flow models performed best in the Interior Mountain and Coastal Mountain regions, with $r^2 > 0.80$, percent bias less than 10% and NSE > 0.85 for most months. The monthly models were less accurate in the Xeric region, with lower r^2 and NSE values and greater bias. However, the monthly models for all regions performed well at predicting flows at omitted sites, with average O/E values of >0.90 for all months and SD <0.50. For maximum 1-day flows, the average O/E value at omitted sites was >0.85, with a SD < 0.4 for the Coastal Mountain and Interior Mountain regions and 0.78 for the Xeric Region.

Estimating degree of regulation (DOR). RF models were also developed to predict mean annual flow at all dam locations (n=753). The suite of geospatial predictor variables were generated for all delineated dam catchments. The annual model was used to predict flows at each dams for 61 water years (1950-2010), which were then averaged to obtain long-term mean annual flow. Units were converted to mean annual runoff (in m^3) and compared with the local and cumulative storage volume (i.e., total reservoir storage in the dam catchment), to estimate

degree-of-regulation (DOR) and cumulative DOR (CDOR) metrics. The model performed well in predicting annual flow values at omitted sites, with high accuracy and limited bias (Table S1.4).

Table S1.1. Performance of monthly and maximum 1-day flow in Coastal Mountain Zone

Model	r^2	Nash Sutcliffe	% Bias	Mean O/E	SD O/E
January	0.92	0.91	3.26	0.94	0.31
February	0.88	0.88	-1.38	0.97	0.31
March	0.93	0.93	0	0.95	0.29
April	0.92	0.92	5.17	0.96	0.3
May	0.84	0.83	9.23	0.94	0.34
June	0.81	0.8	10.04	0.93	0.38
July	0.81	0.75	12.38	0.93	0.31
August	0.85	0.8	12.05	0.85	0.31
September	0.83	0.76	15.47	0.9	0.31
October	0.84	0.84	2.78	0.97	0.4
November	0.88	0.88	-2.1	0.94	0.37
December	0.94	0.94	1.57	0.93	0.32
Maximum 1-day	0.89	0.89	-4.1	0.93	0.39

Table S1.2. Performance of monthly and maximum 1-day flow in Interior Mountain Zone

Model	r^2	Nash Sutcliffe	% Bias	Mean O/E	SD O/E
January	0.72	0.78	3.38	0.98	0.43
February	0.73	0.73	6.74	0.97	0.4
March	0.88	0.86	5.01	0.97	0.3
April	0.87	0.87	3.78	0.97	0.28
May	0.93	0.92	7.3	0.95	0.26
June	0.94	0.94	1.68	0.93	0.31
July	0.90	0.90	-0.29	0.98	0.42
August	0.82	0.81	-9.15	0.95	0.39
September	0.67	0.67	-2.75	0.91	0.42
October	0.84	0.82	-8.33	1.01	0.38
November	0.83	0.82	-6.48	1.05	0.46
December	0.84	0.83	1.75	0.99	0.49
Maximum 1-day	0.91	0.89	-6.2	0.93	0.42

Table S1.3. Performance of monthly and maximum 1-day flow in Xeric Zone

Model	r^2	Nash Sutcliffe	% Bias	Mean O/E	SD O/E
January	0.51	0.48	-1.27	0.96	0.54
February	0.66	0.66	-0.69	0.95	0.49
March	0.56	0.54	-3.34	0.96	0.45
April	0.58	0.55	-5.17	0.95	0.45
May	0.68	0.66	-5.81	0.97	0.4
June	0.67	0.64	-7.64	0.98	0.37
July	0.63	0.57	-11.53	0.98	0.34
August	0.58	0.42	-16.77	0.98	0.35
September	0.61	0.56	-9.72	0.98	0.32
October	0.36	0.33	-12.74	0.97	0.38
November	0.61	0.61	-6.61	0.93	0.46
December	0.75	0.75	-1.27	0.95	0.54
Maximum 1-day	0.74	0.73	-1.06	0.86	0.78

Table S1.4. Performance of annual flow model, used for estimating degree-of-regulation (DOR) at dam locations

Model	r^2	Nash Sutcliffe	% Bias	Mean O/E	SD O/E
Annual flow	0.95	0.94	1.21	0.94	0.30

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Appendix S2. Flow-sensitive fish species list for California

List of California native fish species sensitive to flow alteration. Screening of California dams focused on the 42 species with conservation status of 1 or 2 (endangered or vulnerable, per Moyle et al. 2011).

Common Name	Scientific Name	Conservation Status
Pacific lamprey	*Entosphenus tridentata*	3-Watch List
Klamath River lamprey	*Entosphenus similis*	3-Watch List
River lamprey	*Lampetra ayersi*	3-Watch List
Kern brook lamprey	*Lampetra hubbsi*	2-Vulnerable
Western brook lamprey	*Lampetra richardsoni*	3-Watch List
Northern green sturgeon	*Acipenser medirostris*	2-Vulnerable
Southern green sturgeon	*Acipenser medirostris*	1-Endangered
White sturgeon	*Acipenser transmontanus*	2-Vulnerable
Owens tui chub	*Siphatales bicolor snyderi*	1-Endangered
Blue chub	*Gila coerulea*	3-Watch List
Arroyo chub	*Gila orcutti*	2-Vulnerable
Sacramento hitch	*Lavinia exilicauda exilicauda*	3-Watch List
Monterey hitch	*Lavinia exilicauda harengeus*	2-Vulnerable
Central California roach	*Lavinia symmetricus symmetricus*	3-Watch List
Red Hills roach	*Lavinia symmetricus subspecies*	2-Vulnerable
Monterey roach	*Lavinia symmetricus subditus*	3-Watch List
Tomales Roach	*Lavinia symmetricus subspecies*	3-Watch List
Northern roach	*Lavinia mitrulus*	2-Vulnerable
Sacramento splittail	*Pogonichthys macrolepidotus*	2-Vulnerable
Hardhead	*Mylopharodon conocephalus*	3-Watch List
Sacramento pikeminnow	*Ptychocheilus grandis*	4-Relatively Secure
Sacramento speckled dace	*Rhinichthys osculus subspecies*	4-Relatively Secure
Lahontan speckled dace	*Rhinichthys osculus robustus*	4-Relatively Secure

Owens speckled dace	*Rhinichthys osculus subspecies*	1-Endangered
Santa Ana speckled dace	*Rhinichthys osculus subspecies*	1-Endangered
Lahontan mountain sucker	*Catostomus platyrhynchus*	3-Watch List
Sacramento sucker	*Catostomus occidentalis occidentalis*	4-Relatively Secure
Monterey sucker	*Catostomus occidentalis mnioltiltus*	4-Relatively Secure
Modoc sucker	*Catostomus microps*	1-Endangered
Klamath largescale sucker	*Catostomus snyderi*	2-Vulnerable
Lost River sucker	*Catostomus luxatus*	1-Endangered
Santa Ana sucker	*Catostomus santaanae*	1-Endangered
Shortnose sucker	*Chasmistes brevirostris*	2-Vulnerable
Razorback sucker	*Xyrauchen texanus*	1-Endangered
Longfin smelt	*Spirinchus thaleichthys*	2-Vulnerable
Delta smelt	*Hypomesus pacificus*	1-Endangered
Mountain whitefish	*Prosopium williamsoni*	3-Watch List
Upper Klamath-Trinity fall Chinook salmon	*Oncorhynchus tshawytscha*	2-Vulnerable
Upper Klamath-Trinity spring Chinook salmon	*Oncorhynchus tshawytscha*	1-Endangered
California Coast fall Chinook salmon	*Oncorhynchus tshawytscha*	2-Vulnerable
Central Valley winter Chinook salmon	*Oncorhynchus tshawytscha*	2-Vulnerable
Central Valley spring Chinook salmon	*Oncorhynchus tshawytscha*	2-Vulnerable
Central Valley late fall Chinook salmon	*Oncorhynchus tshawytscha*	1-Endangered
Central Valley fall Chinook salmon	*Oncorhynchus tshawytscha*	2-Vulnerable
Central coast coho salmon	*Oncorhynchus kisutch*	1-Endangered
Southern Oregon Northern California coast coho salmon	*Oncorhynchus kisutch*	1-Endangered
Northern California coast winter steelhead	*Oncorhynchus mykiss*	3-Watch List
Northern California coast summer steelhead	*Oncorhynchus mykiss*	1-Endangered
Klamath Mountains Province winter steelhead	*Oncorhynchus mykiss*	3-Watch List

Klamath Mountains Province summer steelhead	*Oncorhynchus mykiss*	1-Endangered
Central California coast winter steelhead	*Oncorhynchus mykiss*	2-Vulnerable
South Central California coast steelhead	*Oncorhynchus mykiss*	2-Vulnerable
Southern California steelhead	*Oncorhynchus mykiss*	1-Endangered
Kern River rainbow trout	*Oncorhynchus mykiss gilberti*	1-Endangered
Lahontan cutthroat trout	*Oncorhynchus clarki henshawi*	2-Vulnerable
Desert pupfish	*Cyprinodon macularius*	1-Endangered
Owens pupfish	*Cyprinodon radiosus*	1-Endangered
Bigeye marbled sculpin	*Cottus klamathensis macrops*	2-Vulnerable
Lower Klamath marbled sculpin	*Cottus klamathensis polyporus*	3-Watch List
Upper Klamath marbled sculpin	*Cottus klamathensis klamathensis*	3-Watch List
Riffle sculpin	*Cottus gulosus*	3-Watch List
Pit sculpin	*Cottus pitensis*	4-Relatively Secure
Inland threespine stickleback	*Gasterosteus aculeatus microcephalus*	4-Relatively Secure
Unarmored threespine stickleback	*Gasterosteus aculeatus williamsoni*	1-Endangered
Sacramento perch	*Archoplites interruptus*	1-Endangered
Sacramento tule perch	*Hysterocarpus traskii traskii*	3-Watch List
Tidewater Goby	*Eucyclogobius newberryi*	2-Vulnerable

References

Moyle PB, Katz JVE, Quiñones RM. 2011. Rapid decline of California's native inland fishes: a status assessment. Biological Conservation 144: 2414-2423.

Appendix S3. High-priority candidate dams for assessing environmental flow needs for imperiled species conservation and recovery

Dams (n = 181) identified through screening process based on indicators of hydrologic alteration and potential to adversely affect imperiled flow-sensitive fish species (**table S3.1**). An additional 156 dams (**table S3.2**) with evidence of hydrological alteration occur in watersheds from which flow-sensitive species have been locally extirpated and may warrant environmental flows to support the recovery of imperiled fish populations.

Table 3.1. High-priority candidate dams for assessing environmental flow needs for imperiled species conservation

NID	Name	County	River
CA00454	Agnew Lake	Mono	Rush Creek
CA00949	Albaugh No 2	Lassen	Trib Willow Creek
CA00731	Alisal Creek	Santa Barbara	Alisal Creek
CA00204	Alpine	Marin	Lagunitas Creek
CA00226	Anderson Cottonwood	Shasta	Sacramento River
CA00964	Anthony House	Nevada	Deer Creek
CA01412	Arundell Barranca	Ventura	Arundell Barranca
CA00336	Balch Afterbay	Fresno	North Fork Kings River
CA00665	Bean Hollow #2 (De Los Frijoles)	San Mateo	Arroyo De Los Frijoles
CA00666	Bean Hollow #3 (De Los Frijoles)	San Mateo	Arroyo De Los Frijoles
CA00757	Bear Valley	San Bernardino	Bear Creek
CA00191	Big Tujunga No. 1	Los Angeles	Big Tujunga Creek
CA00601	Blodgett	Sacramento	Laguna Creek
CA00207	Bon Tempe	Marin	Lagunitas Creek
CA00088	Bouquet Canyon	Los Angeles	Bouquet Creek
CA00245	Bowman	Nevada	Canyon Creek
CA00802	Boxsprings	Riverside	Box Springs Creek
CA10136	Bradbury	Santa Barbara	Santa Ynez River
CA00284	Bridgeport	Mono	East Walker Rv
CA00126	Calaveras	Alameda	Calaveras Creek
CA00227	Camp Far West	Yuba	Bear River
CA01086	Camp Far West Diversion	Yuba	Bear River
CA00399	Cape Horn Dam (Van Arsdale Reservoir)	Mendocino	South Eel River
CA00378	Caples Lake (Twin Lake)	Alpine	Trib Silver Fork
CA10139	Casitas	Ventura	Coyote Creek
CA00044	Castaic	Los Angeles	Castaic Creek
CA00049	Cedar Springs	San Bernardino	West Fork Mojave River
CA00165	Chabot	Alameda	San Leandro Creek
CA10141	Clear Lake	Modoc	Lost River
CA01119	Clementia	Sacramento	Trib Cosumnes River

CA00214	Copper Basin	San Bernardino	Copper Basin
CA00239	Crocker Diversion (Snelling Diversion)	Merced	Merced River
CA82504	Deer Hill	Modoc	Trib Fletcher Creek
CA00281	Don Pedro Main	Tuolumne	Tuolumne River
CA01248	Dove Canyon	Orange	Dove Creek
CA00068	Dry Canyon	Los Angeles	Dry Canyon Creek
CA00811	Dry Creek	Contra Costa	Dry Creek
CA01240	Edwards Reservoir	Santa Barbara	Trib Gato Creek
CA00806	Elmer J Chesbro	Santa Clara	Llagas Creek
CA10105	Englebright	Yuba	Yuba River
CA10216	Fallen Leaf	El Dorado	Taylor Creek
CA10104	Farmington Dam	San Joaquin	Rock And Littlejohn Creeks
CA00256	Faucherie Lake Main	Nevada	Canyon Creek
CA10148	Folsom	Sacramento	American River
CA00247	French Lake	Nevada	Canyon Creek
CA10154	Friant	Fresno	San Joaquin River
CA00138	Gibraltar	Santa Barbara	Santa Ynez River
CA10156	Glen Anne	Santa Barbara	West Fork Glen Annie Canyon
CA00260	Goodwin	Calaveras	Stanislaus River
CA00089	Grant Lake	Mono	Rush Creek
CA00760	Grass Valley	San Bernardino	Grass Valley Creek
CA10320	Green Tank	Modoc	Trib Fletcher Creek
CA00290	Guadalupe	Santa Clara	Guadalupe Creek
CA10019	Hansen	Los Angeles	Tujunga Wash
CA00694	Hawkins	San Benito	Trib Arroyo De Las Viboras
CA01030	Haynes Res	Shasta	Goose Creek
CA00641	Heenan Lake	Alpine	Tr Efk Carson R
CA00851	Herman, Lake	Solano	Sulphur Springs Creek
CA00848	Hernandez	San Benito	San Benito River
CA00417	Iron Canyon	Shasta	Iron Canyon Creek
CA00325	Iron Gate	Siskiyou	Klamath River
CA00252	Jackson Lake	Nevada	Jackson Creek
CA00254	Jackson Meadows	Nevada	Middle Fork Yuba River
CA00132	James H Turner (San Antonio Reservoir)	Alameda	San Antonio Creek
CA00211	Juncal	Santa Barbara	Santa Ynez River
CA00340	Kerckhoff	Madera	San Joaquin River
CA10160	Keswick	Shasta	Sacramento River
CA00278	La Grange	Stanislaus	Tuolumne River
CA00327	Lake Almanor	Plumas	North Fork Feather River
CA00161	Lake Anza (C L Tilden Park)	Contra Costa	Wildcat Creek
CA00759	Lake Arrowhead	San Bernardino	Little Bear Creek
CA00142	Lake Frey	Solano	Wild Horse Creek
CA00224	Lake Gregory	San Bernardino	Houston Creek

CA00763	Lake Hemet	Riverside	Trib San Jacinto River
CA10131	Lake Oneill	San Diego	Santa Margarita River Offstream
CA00736	Lake Sherwood	Ventura	Potrero Valley Creek
CA10162	Lake Tahoe	Placer	Truckee River
CA10164	Lauro	Santa Barbara	Diablo Creek
CA10165	Lewiston	Trinity	Trinity River
CA00090	Long Valley	Mono	Owens River
CA00887	Lopez	San Luis Obispo	Arroyo Grande Creek
CA00380	Lower Blue Lake	Alpine	Blue Creek
CA00127	Lower Crystal Springs	San Mateo	San Mateo Creek
CA00635	Lower Kinney Lake	Alpine	Tr Silver Creek
CA00664	Lucerne, Lake	San Mateo	Arroyo De Los Frijoles
CA00296	Magalia	Butte	Little Butte Creek
CA00739	Malibu Lake Club	Los Angeles	Malibu Creek
CA10108	Martis Creek	Nevada	Martis Creek
CA00312	Matilija	Ventura	Matilija Creek
CA00459	McBrien	Modoc	Pit River
CA00242	McSwain	Mariposa	Merced River
CA00381	Meadow Lake	Alpine	Trib North Fork Mokelumne
CA00341	Merced Falls	Merced	Merced River
CA01313	Merlo	Sonoma	Fall Creek
CA00248	Milton	Nevada/Sierra	Middle Yuba River
CA01122	Mission Viejo, Lake	Orange	Oso Creek
CA00243	Modesto Res	Stanislaus	Trib Tuolumne River
CA10021	Mojave Dam	San Bernardino	W Fk Mojave River
CA10170	Monticello	Yolo	Putah Creek
CA00216	Morris	Los Angeles	San Gabriel River
CA00155	Municipal	Solano	Trib Suisun Creek
CA00953	Myers	Lassen	Trib Ash Creek
CA00812	Nacimiento	San Luis Obispo	Nacimiento River
CA01029	Nash	Shasta	Trib Stillwater Creek
CA01082	New U San Leandro	Alameda	San Leandro Creek
CA00156	Newell	Santa Cruz	San Lorenzo River
CA10174	Nimbus	Sacramento	American River
CA00299	North Fork (Pacheco Dam)	Santa Clara	Pacheco Creek
CA00674	Notre Dame	San Mateo	Belmont Creek
CA00321	Novato Creek	Marin	Novato Creek
CA00193	Pacoima	Los Angeles	Pacoima Creek
CA00847	Paicines	San Benito	Trib Tres Pinos Creek
CA00297	Paradise	Butte	Little Butte Creek
CA00301	Peoples Weir	Kings	Kings River
CA00208	Peters	Marin	Lagunitas Creek
CA00206	Phoenix Lake	Marin	Ross Creek

CA00128	Pilarcitos	San Mateo	Pilarcitos Creek
CA10112	Pine Flat	Fresno	Kings River
CA00397	Pit No. 4 Diversion	Shasta	Pit River
CA00402	Pit No. 5 Diversion	Shasta	Pit River
CA83281	Pit River Weir	Shasta	Pit River
CA01008	Pomponio Ranch	San Mateo	Pomponio Creek
CA00743	Potrero	Los Angeles	Potrero Valley
CA10179	Prosser Creek	Nevada	Prosser Creek
CA10180	Putah Diversion	Yolo, Solano	Putah Creek
CA00052	Pyramid	Los Angeles	Piru Creek
CA00761	Rancho Cielito	San Bernardino	Trib Chino Creek
CA00011	Rector Creek	Napa	Rector Creek
CA10181	Red Bluff Diversion	Tehama	Sacramento River
CA00921	Renner Sibley Cr	Modoc	Sibley Creek
CA00262	Rodden Lake	Stanislaus	Lesnini Creek
CA00934	Ross No 1	Shasta	Trib Stillwater Creek
CA01351	Rubber Dam 1	Alameda	Alameda Creek
CA01380	Rubber Dam 2	Alameda	Alameda Creek
CA01251	Rubber Dam 3	Alameda	Alameda Creek
CA10202	Salinas	San Luis Obispo	Salinas River
CA00129	San Andreas	San Mateo	Trib San Mateo Creek
CA00813	San Antonio	Monterey	San Antonio River
CA00195	San Dimas	Los Angeles	San Dimas Creek
CA00200	San Gabriel	Los Angeles	San Gabriel River
CA10323	San Justo	San Benito	Offstream
CA00166	San Pablo	Contra Costa	San Pablo Creek
CA10024	Santa Fe	Los Angeles	San Gabriel River
CA00805	Santa Felicia	Ventura	Piru Creek
CA00398	Scott	Lake	Eel River
CA00563	Scout Lake	Mendocino	Trib Berry Creek
CA00669	Searsville	San Mateo	Corte Madera Creek
CA00209	Seeger	Marin	Nicasio Creek
CA10025	Sepulveda	Los Angeles	Los Angeles River
CA10186	Shasta	Shasta	Sacramento River
CA01083	Soulajule	Marin	Arroyo Sausal
CA00873	Sulphur Creek	Orange	Sulphur Creek
CA00461	SX (Essex)	Modoc	Trib Pit River
CA00800	Sycamore	Riverside	Sycamore Canyon
CA01266	Sycamore Canyon	Ventura	Sycamore Can
CA00729	Tejon Storage 2	Kern	Trib Tejon Creek
CA00888	Terminal	San Luis Obispo	Trib Arroyo Grande
CA10114	Terminus (Lake Kaweah)	Tulare	Kaweah River
CA00036	Thermalito Diversion	Butte	Feather River

CA00084	Tinemaha	Inyo	Owens River
CA01123	Trampas Canyon	Orange	Trampas Canyon
CA00956	Tule Lake (Moon Lake)	Lassen	Cedar Creek
CA00265	Tulloch	Calaveras	Stanislaus River
CA00384	Twin Lakes	Alpine	Trib North Fork Mokelumne
CA10197	Twitchell	San Luis Obispo	Cuyama River
CA00385	Upper Blue Lake	Alpine	Blue Creek
CA01145	Upper Oso	Orange	Oso Creek
CA00807	Uvas	Santa Clara	Uvas Creek
CA00770	Vail	Riverside	Temecula Creek
CA00602	Van Vleck	Sacramento	Trib Arkansas Creek
CA00842	Virginia Ranch	Yuba	Dry Creek
CA10303	Warm Springs	Sonoma	Dry Creek
CA10232	Weaver	Nevada	Eastfork
CA00300	West Valley	Modoc	West Valley Creek
CA00904	Westlake Reservoir	Los Angeles	Tree Springs Creek
CA00029	Whale Rock	San Luis Obispo	Old Creek
CA10204	Whiskeytown	Shasta	Clear Creek
CA00586	William, Lake	Napa	Trib Milliken Creek
CA00850	Wood Ranch	Ventura	Trib Arroyo Simi
CA00285	Woodbridge Div	San Joaquin	Mokelumne River
CA00276	Woodward	Stanislaus	Simmons Creek

Table 3.2. Candidate dams for assessing environmental flow needs for imperiled species recovery

NID	Name	County	River
CA01361	Agua Chinon	Orange	Agua Chinon Wash
CA00798	Alessandro	Riverside	Alessandro Creek
CA00289	Almaden	Santa Clara	Almitos Creek
CA00294	Anderson	Santa Clara	Coyote River
CA00266	Beardsley Afterbay	Tuolumne	Middle Fork Stanislaus River
CA00413	Belden Forebay (Caribou Afterbay)	Plumas	North Fork Feather River
CA00835	Berenda Slough	Madera	Berenda Slough
CA00434	Big Creek Dam No. 3a (Huntington)	Fresno	Big Creek
CA00432	Big Creek Dam No. 6	Fresno	San Joaquin River
CA00440	Big Creek Dam No. 7 (Redinger Lake)	Fresno	San Joaquin River
CA00187	Big Dalton	Los Angeles	Big Dalton Wash
CA01075	Big Dry Creek	Fresno	Big Dry Cr & Do
CA00233	Big Sage	Modoc	Rattlesnake Creek
CA10102	Black Butte	Tehama	Stony Creek
CA10135	Boca	Nevada	Little Truckee River
CA00747	Bonita Canyon	Orange	Bonita Creek
CA00566	Bordeaux, Lake	Lake	Trib Bucksnort Creek
CA00524	Branham Flat	Lassen	Branham Creek
CA01098	Bravo Lake Reservoir	Tulare	Wutchumna Ditch
CA10342	Brown Mtn Barrier	Los Angeles	Arroyo Seco
CA00824	Brush Creek	El Dorado	Brush Creek
CA10243	Buchanan	Madera	Chowchilla River
CA00332	Bucks Lake (Bucks Storage)	Plumas	Bucks Creek
CA10103	Burns	Merced	Burns Creek
CA00781	Calavera	San Diego	Calavera Creek
CA00288	Calero	Santa Clara	Calero Creek
CA00173	Camanche Main	San Joaquin	Mokelumne River
CA00817	Camino	El Dorado	Silver Creek
CA01355	Castle	Merced	Canal Creek
CA00067	Chatsworth	Los Angeles	Trib Los Angeles River
CA00158	Cherry Flat	Santa Clara	Penitencia Creek
CA00125	Cherry Valley	Tuolumne	Cherry Creek
CA00418	Chili Bar	El Dorado	South Fork American River
CA01011	Coit	Santa Clara	Trib North Fork Pacheco Creek
CA00104	Conn Creek	Napa	Conn Creek
CA00287	Coyote	Santa Clara	Coyote Creek
CA10201	Coyote Valley Dam	Mendocino	East Fork Russian River
CA00329	Cresta	Plumas	North Fork Feather River
CA00840	Cull Creek	Alameda	Cull Creek

CA10327	Cummings Res No 2	Modoc	Pit River Trib
CA00234	Cuyamaca	San Diego	Boulder Creek
CA00656	Davis No 2	San Joaquin	Trib Calaveras River
CA00043	Del Valle	Alameda	Arroyo Valley
CA00878	Dixon	San Diego	Trib Escondido Creek
CA00537	Donner Lake	Nevada	Donner Creek
CA10144	Dorris	Modoc	Stockdill Slough
CA00929	Dwight Hammond	Siskiyou	Trib Shasta River
CA00120	Early Intake	Tuolumne	Tuolumne River
CA01055	Eaton H. Magoon Lake (Upper Bohn Lake)	Napa	Routan Creek
CA00111	El Capitan	San Diego	San Diego River
CA00486	Enquist	Modoc	Trib Olivers Can
CA10313	Everly	Modoc	Long Branch Cyn
CA01327	Fancher Creek	Fresno	Fancher Cr & Hog Creek
CA00273	Forbestown Diversion	Butte	South Fork Feather River
CA00655	Gilmore	San Joaquin	Trib Mormon Slough
CA00612	Goffinet	Amador	Jackass Creek
CA00675	Grant Company 2	Santa Clara	Arroyo Aguague
CA00333	Grizzly Forebay	Plumas	Grizzly Creek
CA00605	Hamel	Sacramento	Trib Dry Creek
CA00797	Harrison Street	Riverside	Harrison Creek
CA00005	Henderson	Amador	Jackass Creek
CA00702	Hendricks Head Diversion	Butte	Trib Horse Creek
CA00283	Henshaw	San Diego	San Luis Rey River
CA10244	Hidden Dam	Madera	Fresno River
CA00108	Hodges, Lake	San Diego	San Dieguito River
CA00515	Hog Flat	Lassen	Tr Susan River
CA00867	Jackson Creek	Amador	Jackson Creek
CA00232	Jacobs Creek	El Dorado	Jacobs Creek
CA00293	James J. Lenihan (Lexington)	Santa Clara	Los Gatos Creek
CA00706	Jane, Lake	Madera	Trib Hildreth Creek
CA00815	Junction	El Dorado	Silver Creek
CA00698	Kelsey	Merced	Trib South Fork Dry Creek
CA82531	Kern No 3	Tulare	Kern River
CA01307	Kilmer	Tuolumne	Trib Dry Creek
CA00748	Laguna	Orange	Trib San Diego Creek
CA00140	Lake Curry	Napa	Gordon Valley Creek
CA00776	Lake Loveland	San Diego	Sweetwater River
CA00745	Lambert	Orange	Trib Newport Bay
CA01217	Las Llajas	Ventura	Las Llajas Can
CA00516	Leavitt, Lake	Lassen	Tr Susan River
CA00764	Little Lake	Riverside	Trib San Jacinto
CA10166	Little Panoche Detention	Fresno	Little Panoche Creek

CA10020	Lopez	Los Angeles	Pacoima Wash
CA10167	Los Banos Creek Detention Dam	Merced	Los Banos Creek
CA00331	Lower Bucks Lake (Bucks Diversion)	Plumas	Bucks Creek
CA00076	Lower San Fernando (Lower Van Norman)	Los Angeles	San Fernando Creek
CA00644	Lower Twin Lake	Mono	Robinson Creek
CA00387	Lyons	Tuolumne	South Fork Stanislaus River
CA00027	Madera Lake	Madera	Fresno River
CA00443	Mammoth Pool	Fresno	San Joaquin River
CA01211	Mary Street	Riverside	Alessandro Wash
CA00212	Mathews	Riverside	Trib Cajalco Creek
CA00416	McCloud Diversion	Shasta	McCloud River
CA01257	McKays Point Diversion	Calaveras	North Fork Stanislaus River
CA00305	Mockingbird Canyon	Riverside	Mockingbird Canyon
CA01013	Murry	Santa Clara	Mississippi Creek
CA01097	Mustang Creek	Merced	Mustang Creek
CA00863	New Bullards Bar	Yuba	North Yuba River
CA00240	New Exchequer (Lake McClure)	Mariposa	Merced River
CA10246	New Melones	Calaveras	Stanislaus River
CA00035	Oroville	Butte	Feather River
CA00864	Our House	Sierra	Middle Fork Yuba River
CA10111	Owens Dam	Mariposa	Owens Creek
CA00938	Peconom	Lassen	Antelope Val
CA00746	Peters Canyon	Orange	Peters Canyon
CA00801	Pigeon Pass	Riverside	Pigeon Pass
CA83151	Pit No. 7 Afterbay	Shasta	Pit River
CA00328	Poe	Butte	North Fork Feather River
CA00274	Ponderosa	Butte	South Fork Feather River
CA00909	Poway	San Diego	Warren Canyon
CA00799	Prenda	Riverside	Prenda Creek
CA00194	Puddingstone	Los Angeles	Walnut Creek
CA00771	Quail Valley	Riverside	Trib San Jancinto River
CA00765	Railroad Canyon	Riverside	San Jacinto River
CA01215	Ramona	San Diego	Green Val Road Creek
CA00825	Rancho Seco	Sacramento	Trib Hadselville Creek
CA00837	Redbank	Fresno	Redbank Creek
CA00223	Robert A Skinner	Riverside	Tucalota Creek
CA00485	Roberts	Modoc	Trib Pit River
CA00330	Rock Creek	Plumas	North Fork Feather River
CA00509	Round Valley	Lassen	Round Val Cr
CA00833	Ruth Lake (R. W. Matthews)	Trinity	Mad River
CA00620	Salt Springs Valley	Calaveras	Rock Creek
CA00906	San Dieguito	San Diego	Trib Escondido Creek
CA00841	San Lorenzo Creek (Don Castro)	Alameda	San Lorenzo Creek

CA00782	San Marcos	San Diego	San Marcos Creek
CA00113	San Vicente	San Diego	San Vicente Creek
CA00854	Sand Canyon	Orange	Sand Canyon
CA00298	Santiago Creek	Orange	Santiago Creek
CA00109	Savage	San Diego	Otay River
CA01045	Schubin	El Dorado	Trib Webber Creek
CA10324	Seven Oaks	San Bernardino	Santa Ana River
CA00437	Shaver Lake	Fresno	Stevenson Creek
CA00705	Sierra Vista	Madera	Chowchilla River
CA00823	Slab Creek	El Dorado	South Fork American River
CA00271	Slate Creek	Plumas	Slate Creek
CA01250	Smiths Reservoir	Merced	Trib Burns Creek
CA10192	Stampede	Sierra	Little Truckee River
CA10194	Stony Gorge	Glenn	Stony Creek
CA10113	Success	Tulare	Tule River
CA00114	Sutherland	San Diego	Santa Ysabel Creek
CA00775	Sweetwater Main	San Diego	Sweetwater River
CA00401	Tiger Creek Afterbay	Amador	North Fork Mokelumne River
CA01115	Top Cat	Tehama	Trib Brannin Creek
CA10196	Trinity	Trinity	Trinity River
CA00905	Turner	San Diego	Moosa Canyon
CA00112	Upper Otay	San Diego	Proctor Val Creek
CA00291	Vasona Percolating	Santa Clara	Los Gatos Creek
CA00750	Veeh	Orange	Trib San Diego Creek
CA00829	Villa Park	Orange	Santiago Creek
CA01314	Wallace	Calaveras	Trib Bear Creek
CA00482	White	Modoc	Trib Pit River
CA10027	Whittier Narrows Dam	Los Angeles	San Gabriel River
CA00772	Wohlford Lake	San Diego	Escondido Creek
CA82501	Wood Flat	Modoc	North Fork Pit River
CA00796	Woodcrest	Riverside	Woodcrest Creek

Appendix S4. Ranking of candidate dams based on hydrologic, ecological and jurisdictional criteria

Table S4.1 Top 20-ranking dams sorted by storage capacity, seasonal flow alteration, and degree-of-regulation

Storage Capacity (Mm^3)		**Seasonal flow alteration (Pearson's *r*)***		**Degree-of-Regulation (capacity/mean annual inflow)**	
Shasta	5615	Meadow Lake	-0.03	Trampas Canyon	180
Don Pedro Main	2504	Santa Felicia	-0.03	Copper Basin	97
Monticello	1976	Lake Almanor	0.04	Wood Ranch	95
Lake Almanor	1613	Lower Blue Lake	0.07	Woodward	77
Pine Flat	1233	Twitchell	0.08	Paicines	74
Folsom	1203	Iron Canyon	0.10	Westlake Reservoir	74
Lake Tahoe	903	Tinemaha	0.13	Modesto Res	65
Friant	642	Jackson Lake	0.15	Upper Oso	53
Clear Lake	556	Upper Blue Lake	0.18	Bouquet Canyon	51
Warm Springs	470	Lake Tahoe	0.22	Casitas	42
San Antonio	432	James Turner (San Antonio)	0.32	McBrien	40
Nacimiento	419	Iron Gate	0.36	Mission Viejo, Lake	33
Castaic	399	Pit No. 4 Diversion	0.37	Castaic	28
Casitas	313	Calaveras	0.37	Terminal	19
Whiskeytown	297	Thermalito Diversion	0.43	San Andreas	18
Twitchell	296	Lewiston	0.44	Whale Rock	18
Bradbury	253	Lower Crystal Springs	0.46	Lake Arrowhead	17
Long Valley	226	Pit No. 5 Diversion	0.48	Tule Lake (Moon Lake)	13
Pyramid	222	Keswick	0.50	Tejon Storage 2	12
Lake Kaweah	176	Monticello	0.51	Monticello	9

*Correlation between observed and expected (modeled) mean monthly flows, assessed only at dams with downstream gages (n = 252)

Table S4.2 Top 20-ranking dams sorted by number of imperiled flow-sensitive species and native species richness

Imperiled flow-sensitive species richness		**Native species richness**	
Camp Far West Diversion	6	Red Bluff Diversion	21
Red Bluff Diversion	6	Woodbridge Div	19
Camp Far West	6	Camp Far West Diversion	17
Whiskeytown	5	Camp Far West	17
Lake Anza (C L Tilden Park)	5	Lake Anza (C L Tilden Park)	16
Woodbridge Div	5	Whiskeytown	15
Clear Lake	5	Nash	15
Castaic	4	Keswick	15
Nash	4	Herman, Lake	15
Lewiston	4	Anderson Cottonwood	15
Edwards Reservoir	3	Shasta	15
Lauro	3	Nimbus	15
Keswick	3	Folsom	15
Malibu Lake Club	3	Woodward	14
Lucerne, Lake	3	Warm Springs	14
Pine Flat	3	Farmington Dam	14
Farmington Dam	3	Crocker Diversion (Snelling Diversion)	14
Magalia	3	Merlo	14
Paradise	3	Goodwin	14
Trampas Canyon	3	Tulloch	14

Table S4.3 Candidate dams subject to federal FERC or ESA regulations that require environmental flows

Dam Name	**Owner/Operator**
Agnew Lake	Southern California Edison Company
Balch Afterbay	Pacific Gas and Electric Company
Bowman	Nevada Irrigation District
Camp Far West	South Sutter Water District
Cape Horn Dam (Van Arsdale Reservoir)	Pacific Gas and Electric Company
Caples Lake (Twin Lake)	Pacific Gas and Electric Company
Cedar Springs	California Dept Of Water Resources
Clear Lake	U S Bureau Of Reclamation
Don Pedro Main	Turlock Irrigation District
Faucherie Lake Main	Nevada Irrigation District
French Lake	Nevada Irrigation District
Friant	U S Bureau Of Reclamation
Iron Canyon	Pacific Gas and Electric Company
Iron Gate	Pacificorp
Jackson Lake	Nevada Irrigation District
Jackson Meadows	Nevada Irrigation District
Kerckhoff	Pacific Gas and Electric Company
Lake Almanor	Pacific Gas and Electric Company
Lake Tahoe	U S Bureau Of Reclamation
Lower Blue Lake	Pacific Gas and Electric Company
McSwain	Merced Irrigation District
Meadow Lake	Pacific Gas and Electric Company
Merced Falls	Pacific Gas and Electric Company
Milton	Nevada Irrigation District
Monticello	U S Bureau Of Reclamation
Pit No. 4 Diversion	Pacific Gas and Electric Company
Pit No. 5 Diversion	Pacific Gas and Electric Company
Pit River Weir	Pacific Gas and Electric Company
Pyramid	California Department Of Water Resources
Santa Felicia	United Water Conservation District
Scott	Pacific Gas and Electric Company
Shasta	U S Bureau Of Reclamation
Thermalito Diversion	California Department Of Water Resources
Tulloch	South San Joaquin Irrigation District
Twin Lakes	Pacific Gas and Electric Company
Upper Blue Lake	Pacific Gas and Electric Company
Virginia Ranch	Browns Valley Irrigation District
Whiskeytown	U S Bureau Of Reclamation

Table S4.4 Candidate dams ordered by primary purpose designations

Dam Name	Primary Purpose
Englebright	Debris Control
Arundell Barranca	Flood Control
Big Tujunga No. 1	Flood Control
Boxsprings	Flood Control
Dry Creek	Flood Control
Farmington Dam	Flood Control
Hansen	Flood Control
Martis Creek	Flood Control
Mojave Dam	Flood Control
Pacoima	Flood Control
Pine Flat	Flood Control
Prosser Creek	Flood Control
Santa Fe	Flood Control
Sepulveda	Flood Control
Sycamore	Flood Control
Sycamore Canyon	Flood Control
Terminus (Lake Kaweah)	Flood Control
Agnew Lake	Hydroelectric
Balch Afterbay	Hydroelectric
Cape Horn Dam (Van Arsdale Reservoir)	Hydroelectric
Caples Lake (Twin Lake)	Hydroelectric
Don Pedro Main	Hydroelectric
Iron Canyon	Hydroelectric
Kerckhoff	Hydroelectric
Lake Almanor	Hydroelectric
Long Valley	Hydroelectric
Lower Blue Lake	Hydroelectric
McSwain	Hydroelectric
Meadow Lake	Hydroelectric
Merced Falls	Hydroelectric
Nacimiento	Hydroelectric
Nimbus	Hydroelectric
Pit No. 4 Diversion	Hydroelectric
Pit No. 5 Diversion	Hydroelectric
Pit River Weir	Hydroelectric
San Gabriel	Hydroelectric
Scott	Hydroelectric
Tulloch	Hydroelectric
Twin Lakes	Hydroelectric
Upper Blue Lake	Hydroelectric

Whiskeytown	Hydroelectric
Albaugh No 2	Irrigation
Alisal Creek	Irrigation
Anderson Cottonwood	Irrigation
Bean Hollow #2 (De Los Frijoles)	Irrigation
Bean Hollow #3 (De Los Frijoles)	Irrigation
Bear Valley	Irrigation
Blodgett	Irrigation
Bowman	Irrigation
Bridgeport	Irrigation
Camp Far West	Irrigation
Camp Far West Diversion	Irrigation
Casitas	Irrigation
Castaic	Irrigation
Crocker Diversion (Snelling Diversion)	Irrigation
Dove Canyon	Irrigation
Dry Canyon	Irrigation
Edwards Reservoir	Irrigation
Elmer J Chesbro	Irrigation
Faucherie Lake Main	Irrigation
Folsom	Irrigation
French Lake	Irrigation
Friant	Irrigation
Glen Anne	Irrigation
Goodwin	Irrigation
Grass Valley	Irrigation
Guadalupe	Irrigation
Hawkins	Irrigation
Haynes Res	Irrigation
Heenan Lake	Irrigation
Herman, Lake	Irrigation
Hernandez	Irrigation
Jackson Lake	Irrigation
Juncal	Irrigation
Keswick	Irrigation
La Grange	Irrigation
Lake Arrowhead	Irrigation
Lake Gregory	Irrigation
Lake Hemet	Irrigation
Lake Sherwood	Irrigation
Lake Tahoe	Irrigation
Lewiston	Irrigation
Lopez	Irrigation

Lower Kinney Lake	Irrigation
Lucerne, Lake	Irrigation
Magalia	Irrigation
Matilija	Irrigation
McBrien	Irrigation
Merlo	Irrigation
Modesto Res	Irrigation
Monticello	Irrigation
Myers	Irrigation
Nash	Irrigation
North Fork (Pacheco Dam)	Irrigation
Paicines	Irrigation
Paradise	Irrigation
Peoples Weir	Irrigation
Pomponio Ranch	Irrigation
Putah Diversion	Irrigation
Rancho Cielito	Irrigation
Rector Creek	Irrigation
Red Bluff Diversion	Irrigation
Renner Sibley Cr	Irrigation
Rodden Lake	Irrigation
Ross No 1	Irrigation
San Antonio	Irrigation
San Dimas	Irrigation
San Justo	Irrigation
Searsville	Irrigation
Shasta	Irrigation
Sulphur Creek	Irrigation
SX (Essex)	Irrigation
Tejon Storage 2	Irrigation
Tule Lake (Moon Lake)	Irrigation
Upper Oso	Irrigation
Uvas	Irrigation
Vail	Irrigation
Van Vleck	Irrigation
Virginia Ranch	Irrigation
West Valley	Irrigation
Westlake Reservoir	Irrigation
Whale Rock	Irrigation
William, Lake	Irrigation
Woodward	Irrigation
Weaver	Recreation
Clear Lake	Unknown

Deer Hill	Unknown
Fallen Leaf	Unknown
Green Tank	Unknown
Iron Gate	Unkown
Rubber Dam 1	Unknown
Rubber Dam 2	Unknown
Rubber Dam 3	Unknown
Twitchell	Unknown
Warm Springs	Unknown
Woodbridge Div	Unknown
Alpine	Water Supply
Anthony House	Water Supply
Bon Tempe	Water Supply
Bouquet Canyon	Water Supply
Bradbury	Water Supply
Calaveras	Water Supply
Cedar Springs	Water Supply
Chabot	Water Supply
Clementia	Water Supply
Copper Basin	Water Supply
Gibraltar	Water Supply
Grant Lake	Water Supply
Jackson Meadows	Water Supply
James H Turner (San Antonio Reservoir)	Water Supply
Lake Anza (C L Tilden Park)	Water Supply
Lake Frey	Water Supply
Lake Oneill	Water Supply
Lauro	Water Supply
Lower Crystal Springs	Water Supply
Malibu Lake Club	Water Supply
Milton	Water Supply
Mission Viejo, Lake	Water Supply
Morris	Water Supply
Municipal	Water Supply
New U San Leandro	Water Supply
Newell	Water Supply
Notre Dame	Water Supply
Novato Creek	Water Supply
Peters	Water Supply
Phoenix Lake	Water Supply
Pilarcitos	Water Supply
Potrero	Water Supply
Pyramid	Water Supply

Salinas	Water Supply
San Andreas	Water Supply
San Pablo	Water Supply
Santa Felicia	Water Supply
Scout Lake	Water Supply
Seeger	Water Supply
Soulajule	Water Supply
Terminal	Water Supply
Thermalito Diversion	Water Supply
Tinemaha	Water Supply
Trampas Canyon	Water Supply
Wood Ranch	Water Supply