Journal of Environmental Management 136 (2014) 121–131

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Optimizing the dammed: Water supply losses and fish habitat gains from dam removal in California

Sarah E. Null [a,*], Josué Medellín-Azuara [b], Alvar Escriva-Bou [c], Michelle Lent [b], Jay R. Lund [b]

[a] Department of Watershed Sciences, Utah State University, Logan, UT 84321-5210, USA
[b] Center for Watershed Sciences, University of California, Davis, One Shields Avenue, Davis, CA 95616, USA
[c] Departament d'Enginyeria Hidràulica i Medi Ambient, Universitat Politècnica de València, Camí de Vera, s/n., 46022 València, Spain

A R T I C L E I N F O

Article history:
Received 5 August 2013
Received in revised form
26 December 2013
Accepted 20 January 2014
Available online

Keywords:
Dam removal
Water supply
Hydropower
Salmon
Optimization
Tradeoff

A B S T R A C T

Dams provide water supply, flood protection, and hydropower generation benefits, but also harm native species by altering the natural flow regime and degrading aquatic and riparian habitat. Restoring some rivers reaches to free-flowing conditions may restore substantial environmental benefits, but at some economic cost. This study uses a systems analysis approach to preliminarily evaluate removing rim dams in California's Central Valley to highlight promising habitat and unpromising economic use tradeoffs for water supply and hydropower. CALVIN, an economic-engineering optimization model, is used to evaluate water storage and scarcity from removing dams. A warm and dry climate model for a 30-year period centered at 2085, and a population growth scenario for year 2050 water demands represent future conditions. Tradeoffs between hydropower generation and water scarcity to urban, agricultural, and instream flow requirements were compared with additional river kilometers of habitat accessible to anadromous fish species following dam removal. Results show that existing infrastructure is most beneficial if operated as a system (ignoring many current institutional constraints). Removing all rim dams is not beneficial for California, but a subset of existing dams are potentially promising candidates for removal from an optimized water supply and free-flowing river perspective. Removing individual dams decreases statewide delivered water by 0–2282 million cubic meters and provides access to 0 to 3200 km of salmonid habitat upstream of dams. The method described here can help prioritize dam removal, although more detailed, project-specific studies also are needed. Similarly, improving environmental protection can come at substantially lower economic cost, when evaluated and operated as a system.

1. Introduction and rationale

A dam-building era occurred in the American West from the 1930s through the 1970s (Graf, 1999). This heightened economic development by providing reliable irrigation and municipal water supplies, hydropower generation, flood protection, and recreation opportunities (Reisner, 1993). Traditional cost-benefit analyses for dam construction generally did not consider ecosystem degradation, although fish hatcheries for commercially valuable species, such as salmon and trout, were sometimes constructed as a substitute for lost upstream habitat (Waples, 1999).

During the American Environmental Movement of the 1960s and 1970s, laws such as the Endangered Species Act and Clean Water Act were passed to maintain healthy rivers and preserve native species and habitats. By that time, most large rivers were dammed in the American West, requiring water managers to simultaneously regulate water while attempting to maintain healthy, functioning ecosystems. It became apparent that fish hatcheries were imperfect substitutes for wild runs of anadromous fishes and in fact, had introduced a host of problems, including altered run timing, susceptibility to disease, and lowered fitness (Williams et al., 1991). Dams and water development also had fundamentally altered natural flow and sediment regimes, degraded aquatic ecosystems, and harmed native species (Nilsson et al., 2005; Poff et al., 1997; Power et al., 1996). Anadromous fish species, such as Chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*O. kisutch*), steelhead trout (*O. mykiss*), and others, faired particularly poorly, with population declines that coincided with dam-building (Moyle and Randall, 1998).

Our understanding of aquatic and riparian ecosystem processes is improving, as is our ability and desire to manage water resources for both people and ecosystems. However, when we repeatedly fail

* Corresponding author. Tel.: +1 435 797 1338.
E-mail address: sarah.null@usu.edu (S.E. Null).

0301-4797/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jenvman.2014.01.024

to stem or reverse environmental problems, environmental regulation can come to drive water management. This has occurred in California's Bay Delta, where endangered species, altered habitat, and water supply have been on a crash course for decades (Hanemann and Dyckman, 2009; Null et al., 2012; Hanak et al., 2011). Weakening environmental laws is a poor solution if we value aquatic species, ecosystems, and the services they provide, whereas addressing environmental problems directly would allow human objectives to play a larger role in decision-making. Preserving rivers to protect species and habitats is costly (in terms of both money and species) when considered as an afterthought rather than as an explicit objective of water projects. Bernhardt and Palmer (2005) estimate $1 billion US dollars per year are spent on river restoration in the US and restoration costs in California are nearly $6 million/1000 km (km) of streams and rivers. Similarly, the global value of ecosystem services provided by rivers and lakes is estimated to be $1,700,000,000 per year (Costanza et al., 1997).

Given current knowledge of natural ecosystems and the value they provide, water projects would undoubtedly be built differently if they were designed today. It is likely that some existing dams would not be built because biophysical, socio-economic, or geopolitical costs exceed benefits (Pejchar and Warner, 2001; Brown et al., 2009). Also many large dams were built subsequently to smaller dams, creating redundancy and more storage space than water in some watersheds (Fig. 1). For these reasons, removing dams is sometimes attractive for river restoration (Pohl, 2002; Bednarek, 2001; Poff and Hart, 2002). More than 1000 dams have been removed in the U.S. for a variety of reasons, including obsolescence, safety, to avoid costly upgrades for maintenance, hydropower relicensing, to improve water quality and flow for species and habitats, to improve fish passage, and dam failure (Pohl, 2002). In large part, this indicates that dams are subject to changing societal values (Johnson and Graber, 2002) as recent removals on Washington State's Elwha River demonstrate (Gowan et al., 2006; Winter and Crain, 2008). However, prioritizing which dams to remove and the ecological effects of removing them are still emerging fields.

Nearly all dam removal studies assess effects of removing individual dams (some examples include Roberts et al., 2007; Gillenwater et al., 2006; Tomsic et al., 2007; Null and Lund, 2006). While these studies help evaluate the costs and benefits of removing a single structure, more research and better methods are needed to prioritize dams that could be removed within systems and highlight how the remaining system could be re-operated to minimize water scarcity, maintain hydropower generation, maintain flood protection, or improve environmental performance (Kareiva, 2012; Kemp and O'Hanley, 2010). Only a few have put dam removal into a larger decision-making space by representing large

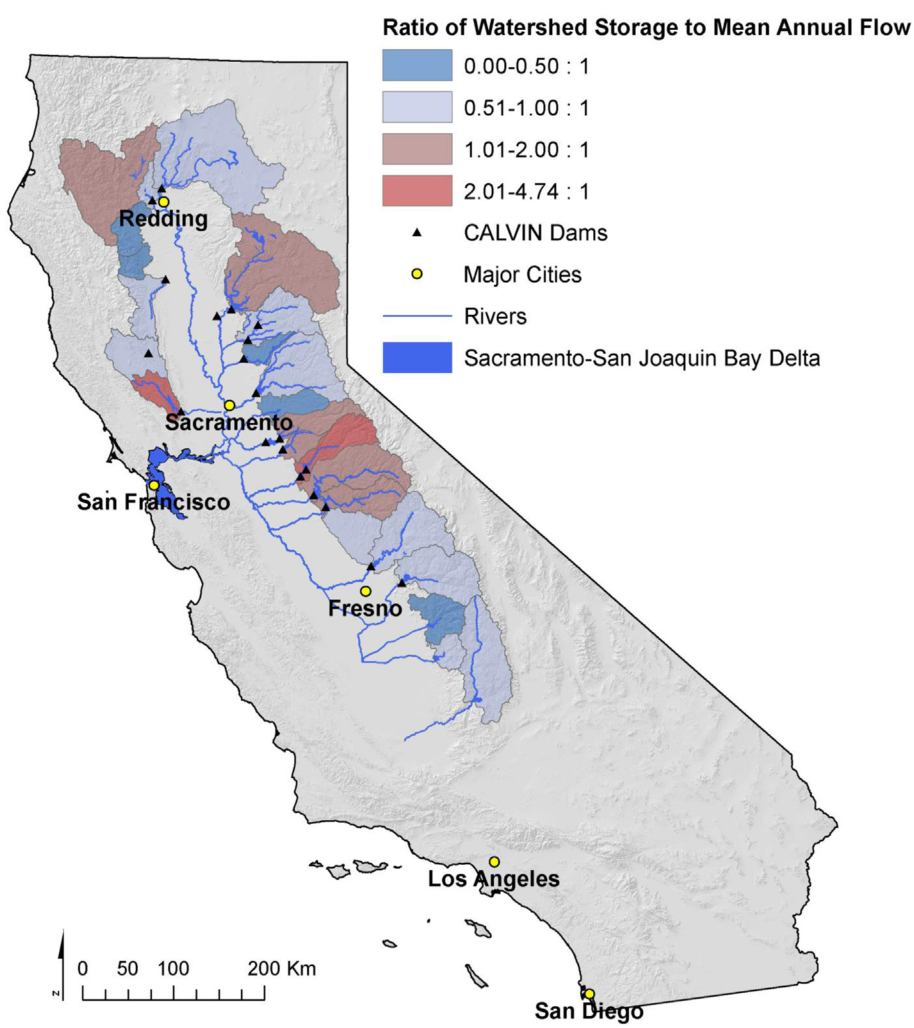

Fig. 1. Ratio of surface water storage capacity to mean annual flow by watershed. Red hues indicate watersheds with more surface storage than mean annual streamflow and blue hues indicate watersheds with less surface water storage than mean annual streamflow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

geographical areas, or human and environmental tradeoffs. Multi-objective optimization has been used to weigh tradeoffs between salmon passage, hydropower generation and water storage in Oregon's Willamette Basin (Kuby et al., 2005), to prioritize removing multiple dams to maximize ecological health and fishing objectives subject to a budget constraint (Zheng et al., 2009), and maximize free-flowing river connectivity for freshwater migratory fishes subject to a constrained budget (O'Hanley, 2011). This work builds on systems analysis theory and research for ranking the value of water supply network elements (Goulter, 1992; Michaud and Apostolakis, 2006).

We evaluate the utility of applying an existing economic-engineering water management optimization model to assess dam removal from multiple, inter-tied water supply systems in California. In regions where water supply systems models have already been developed, removing dams can be evaluated using a systems approach and environmental benefits post-processed. Redundant or less useful dams in the system can be prioritized for removal or additional study, and effects on the rest of the system assessed.

Here we use CALVIN (CALifornia Value Integrated Network) (Draper et al., 2003; Harou et al., 2010) to remove dams systematically and assess system response. The point of this exercise is not to imply that removing all dams is worthwhile, but rather to prioritize for potential removal those that have low economic benefit and large gains in upstream fish habitat. CALVIN has previously been used to analyze water delivery implications of removing O'Shaughnessy Dam, a component of San Francisco's Hetch Hetchy System, located in Yosemite National Park (Null and Lund, 2006). This study highlights opportunities for dam removal in multiple dam systems by analyzing overall water scarcity and water system response, rather than focusing on the effects of removing a single structure. Fish habitat for salmonids is quantified as river length to the next upstream migration passage barrier where trout and salmon were historically present, gradient is less than 12%, mean August air temperature is less than 24 °C, and mean annual flow is greater than 0.028 cms (Lindley et al., 2006). We evaluate trade-offs between fish habitat gains from removing dams and economic losses from reduced water supply and hydropower generation. We also assess groundwater storage reoperation and the marginal cost of additional surface storage when dams are removed. This paper illustrates a method to elucidate how existing water resource infrastructure can be managed most efficiently for people and ecosystems, where opportunities exist to improve environmental conditions by removing dams, and where removing some dams may change the operation and utility of other dams.

2. Study area

California has a Mediterranean climate and receives an average annual 54.5 cm (21.4 in) of precipitation per year (NationalAtlas.gov). Precipitation is highly seasonal with a distinct cool, wet season from November to April and a warm, dry season from May to October. Precipitation falls as both rain and snow (snowline is approximately 1000 m). In mountain regions the snowpack acts as natural water storage, providing snowmelt in spring months when water demands increase. Precipitation is also geographically variable, about $^3/_4$ of the state's precipitation falls north of Sacramento. In contrast, approximately $^3/_4$ of California's 38 million people live south of Sacramento.

A number of large water projects provide surface water storage, and move water generally southward and westward to meet water demands. The federally owned and operated Central Valley Project provides 16,035 million cubic meters (mcm) of water storage in 20 reservoirs, transports water to the San Joaquin and Tulare Valleys with more than 500 miles of canals, has hydroelectric capacity of over 2000 MW (MWh), and provides flood protection and recreation opportunities. The State Water Project owns and operates another 33 reservoirs with a combined 7154 mcm of storage capacity, generates 6.5 million MWh of hydroelectricity (and uses 5.1 million MWh – primarily on pumping), transports water to southern California with over 400 miles of canals, and also provides flood protection and recreation. Cities or local agencies own and operate additional large water projects including East Bay Municipal Utility Districts' Mokelumne Aqueduct, San Francisco's Hetch Hetchy System, and Los Angeles' Colorado Aqueduct and LA Aqueduct. All told, California has over 1500 dams (CDWR, 2000), constructed based variably on need, funding, availability of appropriate sites, or political and institutional might. Two rivers in the state remain undammed - the Cosumnes and Smith Rivers.

The dams removed in this study are all on rivers that drain to the Sacramento–San Joaquin Bay Delta (Bay Delta) so this section focuses on anadromous fish species in California's Central Valley drainage. Approximately 43% of California's total average annual surface runoff flows through the Bay Delta (Fig. 1), linking rivers that drain the west-slope Sierra Nevada Mountains, Central Valley region, and east-slope of coastal mountain ranges with the Pacific Ocean. Anadromous fish species must pass through the Bay Delta to migrate between ocean and freshwater systems. Historically the Central Valley drainage had four runs of Chinook salmon (*O. tshawytscha*) – fall, late fall, winter, and spring. Fall run Chinook salmon is the only run that is currently stable in the Central Valley drainage because fish use low elevation river reaches, although numbers of fish have declined since the 1900s (Yoshiyama et al., 1998). Late fall Chinook are also present in the Sacramento River in reduced numbers, while the spring and winter runs have largely been extirpated from the region (Yoshiyama et al., 1998). Lindley et al. (2006) estimated that 81 distinct populations of steelhead trout (*O. mykiss*) may have existed historically in the Central Valley drainage. Winter-run steelhead are currently present, although populations are confined to rivers below dams throughout the Central Valley (landlocked rainbow trout also persist above dams). The most important causes of population decline for all species and runs are dams that block access to historical habitat, water diversions, out-migrant mortality, water quality impairments, and interactions with hatchery fish (Moyle et al., 2008; Williams et al., 1991; Yoshiyama et al., 1998).

3. Methods

3.1. Economic-engineering optimization model

CALVIN is a large-scale economic-engineering optimization model of California's inter-tied statewide water supply system (Draper et al., 2003). It uses generalized network flow optimization to allocate surface and groundwater resources to urban and agricultural water demand regions on a monthly timestep. CALVIN includes 44 surface reservoirs, 28 groundwater basins, 54 economically-represented urban and agricultural demand areas, 32 hydropower facilities, and connecting infrastructure such as pipelines, canals, and pumping facilities (Fig. 2). This covers more than 85% of the currently populated and irrigated land in the state. Environmental water uses are modeled as constraints and include minimum instream flows for 12 rivers, 6 refuges, Bay Delta outflows, and inflow requirements for Mono and Owens Lakes (Ferreira and Tanaka, 2002).

CALVIN has previously been used to identify promising improvements to California's water management, including climate change effects and adaptations (Connell-Buck et al., 2011; Medellín-Azuara et al., 2008; Tanaka et al., 2006), water scarcity

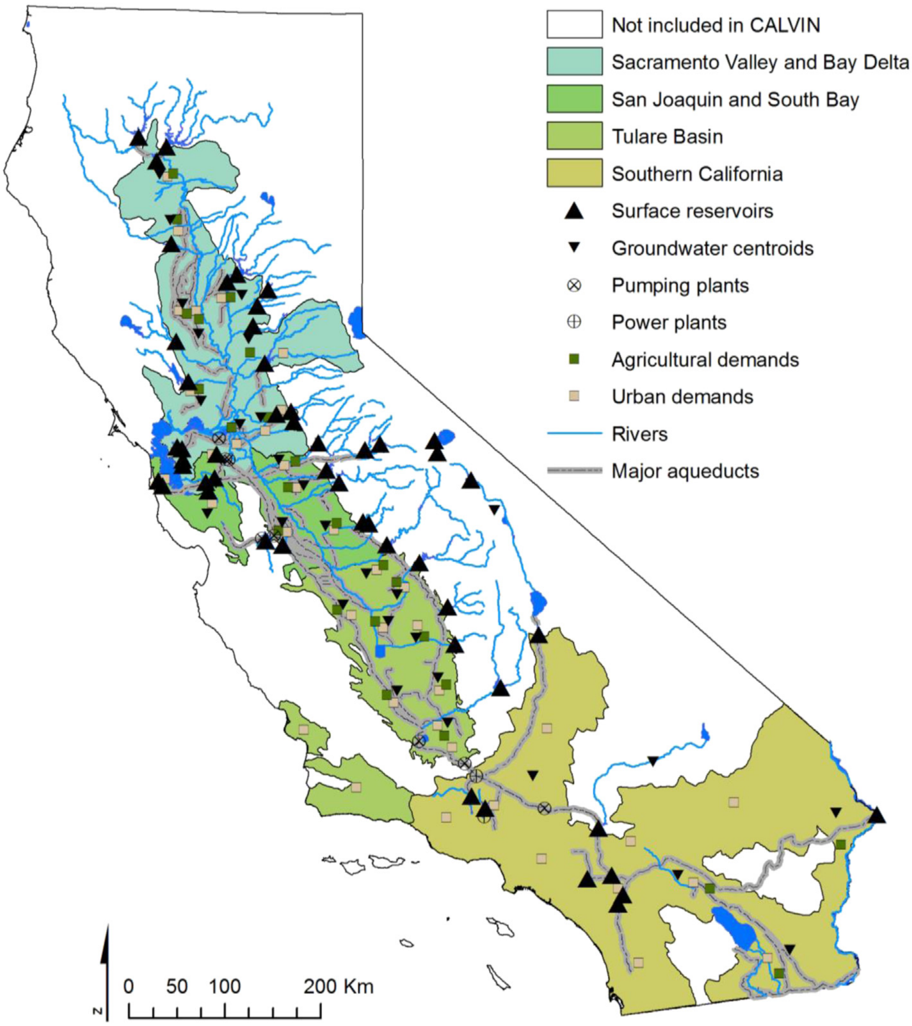

Fig. 2. California's statewide water supply network representation in CALVIN.

and economic consequences from a prolonged, severe drought in California (Harou et al., 2010), regulatory and operational alternatives for the Sacramento–San Joaquin Delta (Lund et al., 2010; Tanaka et al., 2011), water supply analysis for restoring the Colorado River Delta (Medellín-Azuara et al., 2007) and removing O'Shaughnessy Dam from Hetch Hetchy Valley in Yosemite National Park (Null and Lund, 2006).

3.1.1. *Mathematical representation*

CALVIN uses the Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM) software for its optimization solver (USACE, 1999) and represents the water system as a network of nodes and arcs. The objective function of CALVIN is to minimize total economic cost, which is water scarcity to urban and agricultural demand regions and operational costs. It is represented mathematically as:

$$\text{Minimize } Z = \sum_i \sum_j c_{ij} X_{ij} \tag{1}$$

where Z is the total cost (US dollars) of flows throughout the network, c_{ij} is economic costs (US dollars) on arc ij, and X_{ij} is flow from node i to node j (mcm/month) in space and time. Water scarcity is the difference between the volume of water that is demanded in an area if available (a target demand) and the volume of water that is actually delivered. Water scarcity occurs when target demands are not met, and scarcity costs are estimated from the integral between target and delivered water volumes below a water demand curve.

Agricultural and urban water demands are represented with economic penalty functions for the year 2050. Economic penalty functions are convex and increase as water deliveries decrease to represent economic losses when target water deliveries are not met. Urban water demand curves assume a statewide population of approximately 54 million Californians (2012 population was 38 million) (Landis and Reilly, 2003). An additional assumption is that urban water conservation will lead to a reduction from 908 to 837 L of water per person per day (Jenkins, 2004). Agricultural water demands were estimated with the Statewide Agricultural Production model (SWAP, Howitt et al., 2012), which maximizes agricultural profits regarding production technology, cropped acreage, and irrigation decisions. Agricultural water demand estimates for 2050 include agricultural land conversion from increasing urbanization (Landis and Reilly, 2003), technological improvements that increase crop yields, and adaptations such as warmer climate-tolerant crops and higher value crops (Medellín-Azuara et al., 2011).

The objective function is constrained by conservation of water mass through the model (Eq. (2)), physical capacities of infrastructure and natural channels (Eqs. (3) and (4)), and environmental water demands such as minimum instream flows or refuge demands (represented as upper or lower bounds, Eqs. (3) and (4), respectively). These are expressed mathematically as:

$$\sum_i X_{ji} = \sum_i a_{ij} X_{ij} + b_j \quad \text{for all nodes } j \tag{2}$$

$$X_{ij} \le u_{ij} \quad \text{for all arcs} \tag{3}$$

$$X_{ij} \ge l_{ij} \quad \text{for all arcs} \tag{4}$$

where X_{ji} is the flow from node j to node i (mcm/month), X_{ij} is the flow from node i to node j (mcm/month), a_{ij} is gains or losses on flows in arc ij (mcm/month), b_j is external inflows to node j (mcm/month), u_{ij} is the upper bound on arc ij (mcm/month), and l_{ij} is the lower bound on arc ij (mcm/month).

Hydropower is estimated using average monthly wholesale prices, which vary monthly between 1.8 and 3.0 cents/kWh with higher prices in summer and lower prices in winter and spring. This allows hydropower to be computationally feasible for inclusion in CALVIN, but eliminates distinctions between operating hydropower facilities for peaking, intermediate, and base load power generation. This method likely underestimates economic benefit from hydropeaking facilities and overestimates benefit from base load facilities. For a detailed description of hydropower representation in CALVIN see Ritzema (2002).

Model results include monthly time series of optimized flow through each arc, reservoir storage, and water allocations to urban and agricultural demand regions to maximize total economic benefit. Generalized network flow optimization could be applied to any location by estimating local boundary inflows, economic demand functions for water demand regions, and infrastructure topology and capacities. Yeh (1985) and Wurbs (1996) present network flow optimization theory and provide examples of other water resources applications.

3.1.2. Calibration

Inputs for CALVIN include data that were collected at different times, by different agencies, for different purposes, and that were not explicitly intended to be integrated. Thus calibration included resolving data discrepancies from multiple sources. The calibration process in CALVIN is detailed in Jenkins (2001) and consists of four steps: 1) an uncalibrated physical model with un-reconciled surface and groundwater hydrology, demands and deliveries; 2) adjustment of agricultural reuse, return flows and agricultural demands; 3) adjustment of surface water inflows to match streamflows in existing simulation models; and 4) a calibrated model matching existing surface and groundwater models inflows and deliveries.

CALVIN was originally calibrated for 2020 conditions. Adjustments under steps 2 and 3 above include increasing (usually) agricultural water demands to reflect observed water deliveries, adjusting water reuse coefficients and return flows (usually decreasing them), and by adding or subtracting boundary flows to eliminate infeasibilities, account for reservoir evaporation, and correct discrepancies in data from multiple sources. Calibrated CALVIN results match the water demands and hydrologies for California as represented by the California Department of Water Resources' DWRSIM model, the US Bureau of Reclamation (1997), and the 1997 CVGSM groundwater model. Furthermore, CALVIN water demand and hydrology results are comparable to other large-scale California models, such as CALSIM water resources simulation model (CALSIM webpage, 2002). Net calibration flows in CALVIN are relatively small: 68 taf/yr and 55 taf/yr for the Sacramento and San Joaquin Valleys respectively (Jenkins, 2001) with some larger flows for the Tulare Lake basin. These calibration flows represent a small proportion of the rim inflows in the entire Central Valley and match closely with existing hydrologic simulation models.

3.1.3. Climate-adjusted hydrology

Warm and dry climate estimates are from the Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 model using the A2 emissions scenario, with a 30-year period that was centered on 2085. These data were downscaled using the bias correction and spatial downscaling (BCSD) method (Maurer and Hidalgo, 2008). A warm, dry climate is a worst-case scenario in terms of water supply and results in an average statewide temperature increase of 4.5 °C and a 27% precipitation decrease by the end of the century (Cayan et al., 2008).

CALVIN models 72 years of hydrology (1921–1993), which was climate-adjusted by linking GFDL CM2.1 streamflows with CALVIN rim inflows, then applying perturbation ratios to the historical rim inflows (Connell-Buck et al., 2011; Medellín-Azuara et al., 2008; Zhu et al., 2005). This method accounts for changes to streamflow magnitude and timing from climate change and also preserves historic hydrologic variability, but does not account for changing hydrologic variability from climate change. Reservoir evaporation, groundwater inflows and net local accretions were also adjusted for climate change. Statewide, precipitation was reduced by 27%, rim inflows reduced by 28%, reservoir evaporation increased by 37%, groundwater inflows (from deep percolation) reduced by 10%, and net local accretions reduced by 104% (Connell-Buck et al., 2011). See Medellín-Azuara et al. (2008) and Connell-Buck et al. (2011) for a more complete description of climate-adjusted hydrology.

3.2. Fish habitat estimates

Suitable fish habitat is quantified as the river length (km) between a removed dam and the next barrier upstream. Downstream habitat is not considered to change with dam removal (although flow patterns would likely change). Suitable habitat was defined using criteria from Lindley et al. (2006) for steelhead trout, where mean annual flow is greater than 0.028 m^3/s, gradient is less than 12%, mean August air temperature is less than 24 °C, and the area supported anadromous fish historically (Knapp, 1996). Increased discharge has been shown to increase density or abundance of steelhead trout (Harvey et al., 2002) and Chinook salmon (Stevens and Miller, 1983), and mean annual discharge of 0.028 m^3/s was used as a lower bound in Lindley et al. (2006) using a USGS 10 m digital elevation model. Steelhead are most common in systems with gradients less than 6%, although are present of gradients up to 12% (Burnett, 2001; Engle, 2002). Air temperature data are originally from PRISM (Gibson et al., 2002) and 24 °C is the maximum average weekly thermal tolerance for both Chinook salmon and steelhead trout (Eaton and Scheller, 1996), although these species can tolerate warmer temperatures for short periods of time (Myrick and Cech, 2001). Suitable fish habitat spatial data were developed by Lindley et al. (2006) to estimate historical populations of Central Valley steelhead.

A spatial dataset of dams that are larger than 1.2 mcm (1 thousand acre feet [taf]) within the jurisdiction of California (CDWR, 2000) or federal jurisdiction (USACE, 1998) were snapped to river segments using ArcGIS to represent barriers to fish passage upstream of removed dams. Then accessible river length (including tributaries) was summed between each removed dam and the next dam upstream. This method includes only state and federal dams and ignores other passage barriers (such as small or private dams, weirs, culverts, road crossings…). Our method likely overestimates suitable habitat because the total length of all reaches with suitable conditions are summed, even if they do not connect – which could provide habitat for landlocked fish such as rainbow trout, but not anadromous species which need continuous habitat – such as steelhead trout. However, this method ignores adjacent riparian and floodplain habitat that would be enhanced following dam removal.

We assumed that fish passage exists downstream of each dam removed in our study (or that passage would be provided prior to dam removal). We further assume than no negative effects of the structure remain following a dam removal – in reality, rivers could have poor conditions following dam removal from sediment transport, water quality problems, or other impairments. A fish production model that explicitly represents the life histories of anadromous fishes would better represent the benefits of dam removal, but is outside the scope of this study. Finally, fish habitat is not explicitly included in optimization, but is evaluated preliminarily as the tradeoff between economic impacts of removing dams and length of accessible fish habitat above removed dams.

3.3. Model runs

We completed 19 model runs for warm and dry climate conditions. In each model run, a different dam is removed (two dams are removed in a few cases if both are in the region that historically supported anadromous fishes, discussed further below). The removed dams are generally *rim dams* in California parlance – large multipurpose dams at low elevations of each tributary to the Sacramento or San Joaquin River (Figs. 1 and 3). Results are compared to a warm dry climate base case that includes all dams and which is discussed in depth in Connell-Buck et al. (2011) and Medellín-Azuara et al. (2008). All runs assume an intertie links New Don Pedro with the Hetch Hetchy Aqueduct (Null and Lund, 2006). No other infrastructure changes were made in any model runs.

In addition, eight runs compared dam removal with historical conditions (historical climate and year 2050 water demands). We completed these runs to highlight water scarcity and other economic costs that are incurred from removing dams with warm and dry climate conditions versus historical conditions. Historical dam removal runs are compared with a historical base case run that includes all dams, which is discussed further in Connell-Buck et al. (2011). Overall, results focus on model runs that use warm and dry climate conditions so that dam removal results are pertinent for future rather than outdated, historical conditions, although historical runs are sometimes included for comparison.

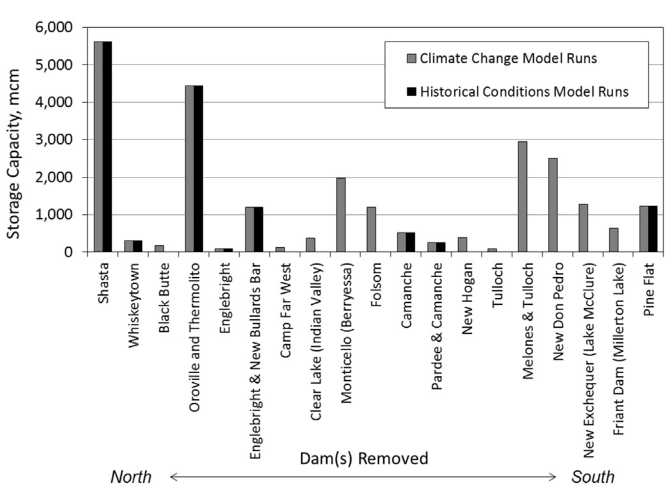

Fig. 3. Climate change and historical conditions model runs with storage capacity (CDWR, 2000) removed from base case – some dam removals were only examined for future drier climate conditions.

Environmental water demands, which are modeled as constraints in CALVIN to remove them from economic valuation, were often relaxed or removed so models reached a feasible solution (Table 1). Modeled environmental constraints include minimum instream flows in rivers as well as flow to fish and wildlife refuges.

CALVIN mostly includes only rim dams, although four rivers are modeled with multiple dams removed, usually where a smaller dam exists downstream from a rim dam (e.g., Feather, Yuba, and Stanislaus Rivers) or where few dams exist on the river (e.g., Mokelumne and Tuolumne Rivers). Model runs with more than one dam removed include the Feather (Oroville and Thermolito Dams), Yuba (Englebright and New Bullards Bar Dams), Mokelumne (Pardee and Camanche Dams) and Stanislaus (Tulloch and Melones Dams) Rivers. On the Feather River, Thermolito is a re-regulating reservoir and we assumed it would not be removed without Oroville. The dams located upstream of New Don Pedro on the Tuolumne River were too high in elevation to have had historical anadromous fisheries and thus, multiple dam removals were not modeled for that river. It is outside the scope of this study to analyze restoring entire rivers or watersheds to unregulated conditions.

4. Results

4.1. Water scarcity and scarcity costs

Optimized water deliveries are compared to target demands in urban and agricultural regions to estimate water scarcity and scarcity costs. Fig. 4 shows statewide urban and agricultural water scarcity for each model run with a dam removed. Historical base case and historical dam removal runs are included for comparison with climate change conditions to show the relative proportion of water scarcity that occurs from climate change versus water scarcity from removing dams. In all runs, urban demand regions have a higher willingness to pay for water, and for this reason, they typically incur less water scarcity than agricultural regions, where senior water rights holders would likely sell water to urban regions. This pattern of cost minimizing water scarcity is common in previous CALVIN research (Draper et al., 2003; Medellín-Azuara et al., 2008; Tanaka et al., 2006; Harou et al., 2010; Connell-Buck et al., 2011).

Overall for the historical base case, agricultural water scarcity is 1074 mcm and urban water scarcity is 39 mcm, with 96% of agricultural target demands and 99.8% of urban target demands met

Table 1
Minimum instream flow (MIF constraints removed for models to reach a feasible solution.

Watershed	Model run	Removed MIF (cms)			Number of modeled reaches with MIFs
		Min	Max	Avg	
Sacramento	Shasta	115	173	124	4
Clear Creek	Whiskeytown	93	173	100	2
Stony Creek	Black Butte	113	142	122	1
Feather	Oroville & Thermolito	28	48	37	2
Yuba	Englebright & New Bullards Bar	2	12	7	2
American	Folsom	7	85	46	3
Mokelumne	Camanche	0	13	3	4
Mokelumne	Pardee & Camanche	0	13	3	4
Calaveras	New Hogan	0	0	0	2
Stanislaus	Melones & Tulloch	2	83	8	1
Merced	New Exchequer (Lake McClure)	0	6	3	2

(target water demands are 29,755 mcm and 15,798 mcm for statewide agricultural and urban demand regions, respectively). Removing Shasta Dam with historical climate and population conditions reduces deliveries to agricultural regions to 94% of target deliveries. Removing dams never changes urban deliveries with historical conditions. This means that when water management is optimized in California, there is ideally enough surplus storage so average annual water scarcity does not change for urban demand regions, and agricultural demand regions are reduced only when Shasta Dam, the state's largest reservoir, is removed.

With base case climate change conditions (assuming a warm and dry climate), both agricultural and urban water scarcity are anticipated to increase, as described in Connell-Buck et al. (2011). The climate change conditions base case run suggests 68% of target demands may be delivered to statewide agricultural regions and over 99% of target demands may be delivered to statewide urban regions. Removing dams with climate change conditions increases water scarcity, so that deliveries to agricultural demand regions are reduced by 0–6%, and deliveries to urban demand regions are reduced by up to 0.2–0.4%. Removing Shasta or Oroville Dams increases water scarcity most with future climate change conditions. Water scarcity is actually reduced from the climate change base case in some runs because minimum instream flows, which are modeled as constraints, were relaxed when dams were removed (Table 1). The striking result from Fig. 4 is that more water scarcity is incurred to agricultural and urban demand areas from the effects of climate change than from removing individual dams.

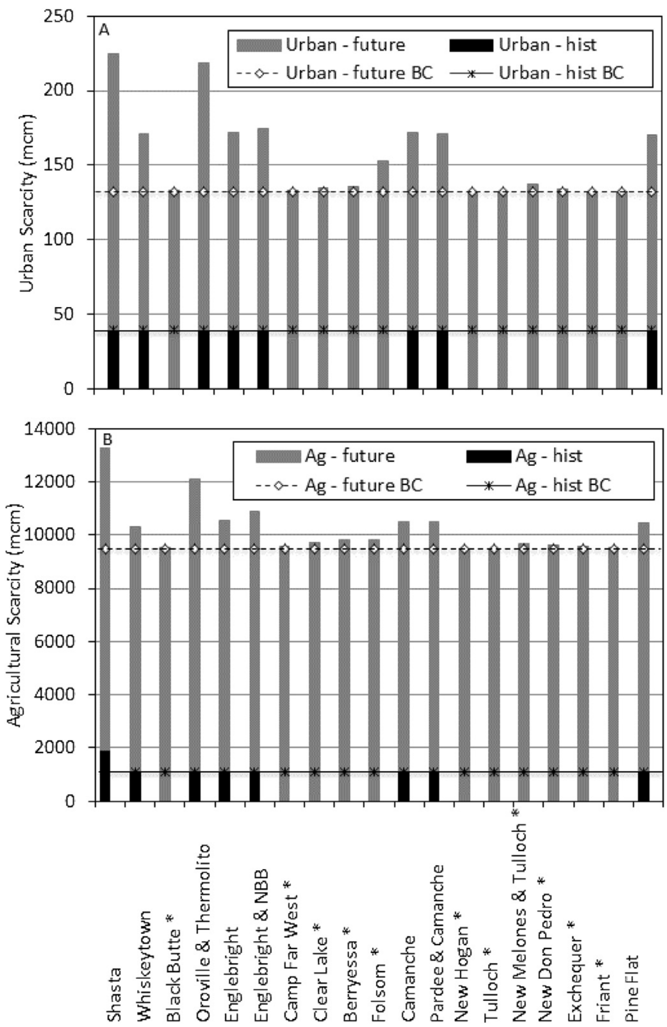

Fig. 4. Historical and future climate change urban water scarcity (A) and historical and future climate change agricultural water scarcity (B) for each dam removed (note scale change between figures). Horizontal lines indicate historical and climate change base case scarcity for comparison (BC = base case, NBB = New Bullards Bar). Asterisks indicate that no model run was completed for historical conditions.

4.2. Tradeoffs between water deliveries and fish habitat

Tradeoffs between total statewide agricultural and urban water delivery losses and fish habitat gains are compared using water delivery data from CALVIN and spatial steelhead habitat data from Lindley et al. (2006). Fig. 5 shows the tradeoff curve for dam removal runs with climate change conditions. Points toward the top right show dams that could be removed with small reductions in water deliveries and considerable fish habitat gains. Points to the bottom left indicate largely reduced water deliveries and small habitat gains. Total statewide agricultural and urban water deliveries are 45.6 billion cubic meters (bcm) and a 5% reduction is a loss of approximately 2282 mcm of delivered water. Whiskeytown, Pine Flat, Pardee and Camanche, or Englebright Reservoirs are less valuable for water supply and removing these dams may be promising to increase available habitat for anadromous fish or other migratory aquatic species. Our results mirror previous research which has identified Englebright Dam in the Yuba watershed as candidate for removal to provide access to spawning habitat for Chinook salmon and steelhead trout (James, 2005). However, the primary purpose of Englebright Dam is to store sediment following decades of hydraulic mining in California (James, 2005), which was not an objective of our study, thus sediment storage benefits of reservoirs were ignored here. Similarly, Whiskeytown acts as a way-station and conduit between the Trinity River and Sacramento River systems and its function is less about mass storage than conveyance and operational storage.

We reiterate that in model runs where Whiskeytown or Pardee and Camanche Dams were removed, minimum instream flows were relaxed or removed as discussed above and in Table 1. CALVIN represents of real-world conditions in this sense – if dams were removed, minimum instream flows requirements would likely not be maintained with free-flowing rivers returning to a more natural hydrograph. Evaluating the environmental benefit of reservoir releases to provide minimum instream flows versus improving access to upstream habitat and a natural hydrograph from removing dams

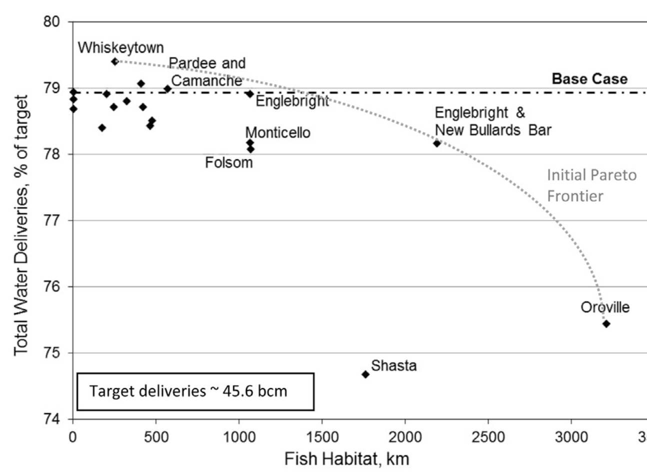

Fig. 5. Tradeoff between total water deliveries and fish habitat with dams removed for climate change conditions (some dams not labeled so figure is readable). Water deliveries may increase with dam removal when minimum instream flow constraints are removed.

is outside the scope of this study, but more research is needed on this topic to highlight tradeoffs between competing environmental water demands.

A Pareto possibility frontier curve is beginning to take shape in Fig. 5 and could be honed by additional research to ensure that both economic water benefits (e.g., water supply) and environmental benefits (e.g. fish habitat and production) are optimized by existing and future infrastructure to most efficiently use water resources for both objectives. Typically human objectives and environmental objectives are analyzed separately – making it difficult to distinguish the Pareto tradeoff curve and identify decisions to use water resources most efficiently for multiple human and environmental objectives.

To illustrate this point, we linearly regressed removed reservoir capacity against additional water scarcity with climate change conditions (Fig. 6). Water scarcity in Fig. 6 is water demands for which users would be willing to pay for water minus water deliveries – so the *y* axis is Fig. 6 is the inverse of the *y* axis in Fig. 5. The Pearson correlation is 0.886, indicating lost reservoir capacity and increased water scarcity are positively correlated, although the relationship is not perfect. The slope of the regression is 0.32 so as reservoir capacity changes by 1 unit, total water scarcity changes by 0.32 units. For the science of modeling removing dams, this means that reservoir capacity is not a perfect proxy for water scarcity and considering only reservoir capacity for removing dams could overestimate effects of removal because it does not account for diminishing marginal returns (where, say, the millionth acre foot of storage is less valuable than the 1st acre foot of storage). Including the economic costs and benefits of water management is necessary to improve understanding of the effects of removing dams. This is a benefit of our approach and a benefit of applying economic-engineering water management models to analyzing removing dams.

4.3. Change to groundwater storage and the marginal value of additional surface storage

CALVIN results include conjunctive use between surface and groundwater storage for groundwater basins that can be recharged. To better understand groundwater storage changes from removing dams with climate change hydrology, we include box plots of total annual change in system-wide groundwater storage from the climate conditions base case (Fig. 7). The ends of the whiskers (the years with the greatest positive and negative total annual change in groundwater storage) generally straddle zero and show that more water may be stored or withdrawn from groundwater basins with

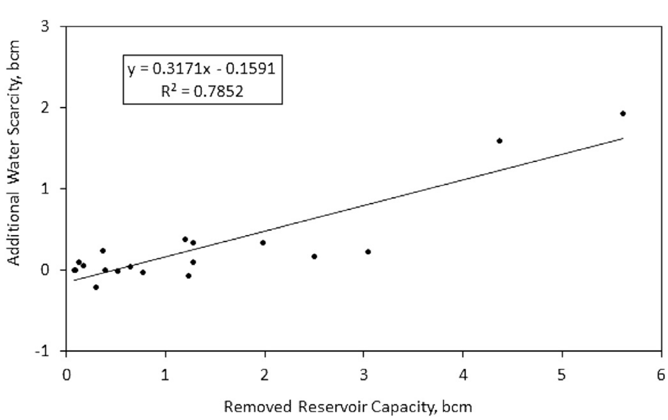

Fig. 6. Correlation between removed reservoir capacity and additional water scarcity with climate change conditions. Water scarcity may decrease with dam removal when minimum instream flow constraints are removed.

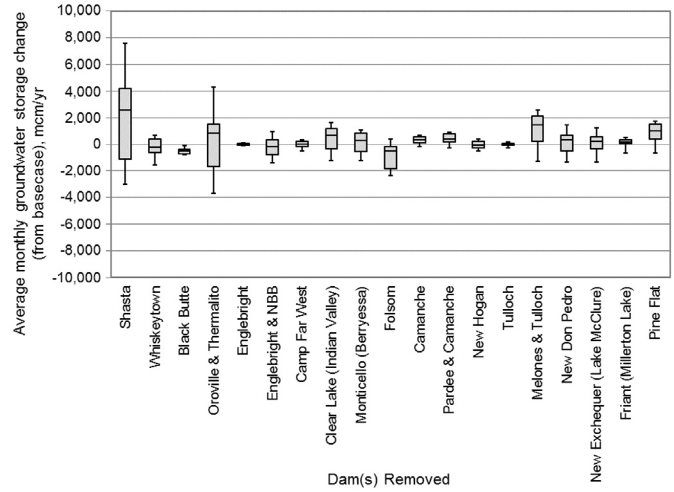

Fig. 7. Total annual groundwater storage change with climate change base case conditions for each dam removed (NBB = New Bullards Bar).

dam removal. This suggests that reductions in surface water storage may be partially offset by conjunctive use strategies and change in groundwater storage can vary considerably when surface reservoirs are removed. In fact, variability in total annual groundwater storage is related to the size of the surface reservoir removed. Removing very large Shasta or Oroville Reservoirs causes *average* total annual groundwater storage to increase with lots of variability between different years. When very small surface reservoirs are removed (for example Black Butte, Englebright, or Tulloch Reservoirs), change in total annual groundwater storage is negligible. Results indicate that groundwater storage increases because storage is valuable to the system; when surface reservoirs are removed, additional storage potential in conjunctive groundwater basins could be utilized.

Analyzing the marginal cost of additional surface storage where dams have been removed helps identify locations where the first additional unit of surface storage is most valuable. For the historical base case, the marginal cost of additional storage varies for each reservoir from $0/mcm to nearly $27/mcm ($0 – $33 per thousand acre feet), but is $0 for all reservoirs for the climate change base case. Fig. 8 shows the marginal cost of additional storage for each

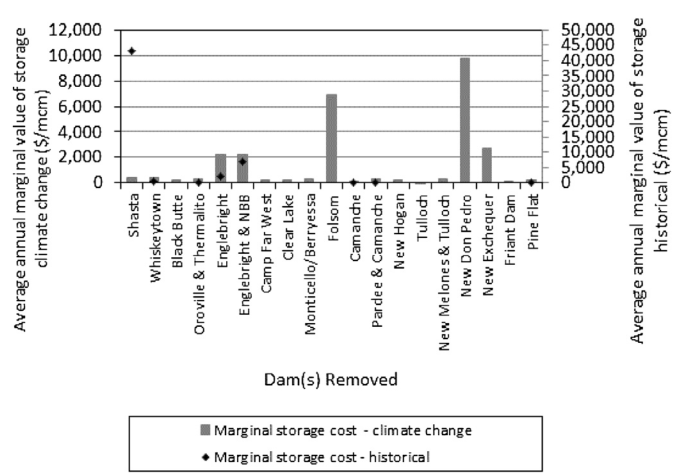

Fig. 8. Average annual marginal value of storage for removed dams with climate change conditions (solid columns on left axis) and for select removed dams with historical conditions (black points on right axis).

dam removed with climate change and with historical conditions. The figure shows that additional reservoir storage when dams have been removed is an order of magnitude greater with historical conditions than climate change conditions. With warm and dry climate change, California's intertied water system is short of water, but not short of storage space – even when some dams have been removed. Overall warmer and drier conditions with climate change model runs make additional reservoir storage less valuable. Similar results have been described using CALVIN results in Null and Lund (2006) for Hetch Hetchy Reservoir. This implies that building new dams is a poor adaptation for a warmer and drier California climate.

4.4. Hydropower losses

System-wide average annual hydropower revenue for the historical base case is $385 million/year (M/yr) and is reduced to $262 M/yr for the climate change base case (Fig. 9). As noted in the previous section, modeling suggests that less water will be stored and released with future climate change, which reduces hydropower generation. This finding is discussed in more detail in Medellín-Azuara et al. (2008) and Connell-Buck et al. (2011). Removing dams in California reduces hydropower generation further. The largest reduction in hydropower generation is from removing Shasta Dam, which lowers total system-wide hydropower revenue to $328 M/yr with historical conditions and $223 M/yr with climate change conditions. Removing some dams does not significantly change hydropower revenue because the dam has little or no hydropower capacity.

Similar to Fig. 5, tradeoffs sometimes exist between total system hydropower generation with climate change conditions and fish habitat gains using spatial steelhead habitat data from Lindley et al. (2006) (Fig. 10). Points toward the top right result in more minor reductions to total hydropower generation but would provide considerable fish habitat with dam removal. For this reason, many points are clustered along the climate change base case of $261.78 M/yr in hydropower generation. Englebright, New Don Pedro, and New Melones and Tulloch may be promising for removal if only hydropower generation tradeoffs are evaluated with fish habitat gains.

5. Limitations

Like all models, CALVIN simplifies real-world conditions – which both limits the model and makes it useful. Improving input data and understanding of California's water system would enhance model performance. CALVIN ignores political, institutional, and legal considerations of water allocations to highlight inefficiencies of the physical water system, rather than inefficiencies of how people choose to operate the system. CALVIN maintains reservoir flood storage rules, but does not consider flood protection in optimization. It also does not consider recreation benefits of rivers or reservoirs. As mentioned in the methods section, CALVIN includes environmental water deliveries to rivers and refuge areas as constraints, which removes them from decision-making. Finally, CALVIN operates with perfect foresight, meaning the model can optimize for flood and drought periods, so results presented here depict a best case scenario for water management. For this dam removal analysis, we analyze economic benefits that are lost or reduced from removing dams, although lost benefits would not be uniform throughout the state. Cities and agricultural regions near dams removed would be more affected than farther removed areas. We did not consider the cost of decommissioning dams. In addition, there is some benefit of redundancy in water systems for maintenance, system reliability with variable hydrologic conditions, or to account for failure (Michaud and Apostolakis, 2006). The value of surface storage redundancy is ignored here. For a more thorough discussion on CALVIN's limitations, see (Draper et al., 2003; Connell-Buck et al., 2011; Medellín-Azuara et al., 2008).

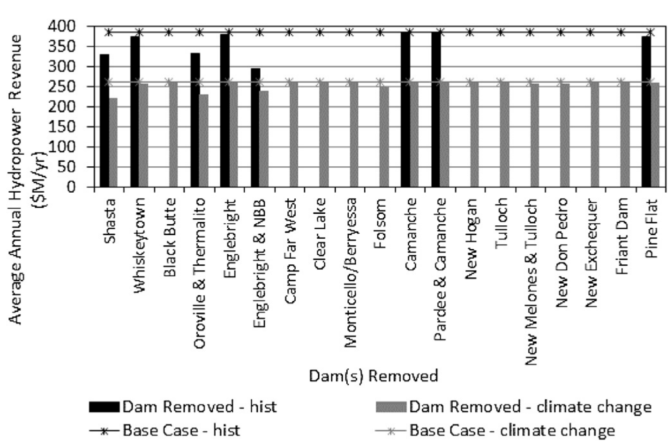

Fig. 9. Average annual hydropower revenue ($M/yr) for the historical base case (black line), select historical dam removal runs (black bars), future climate base case (gray line), and future climate dam removal runs (gray bars) (NBB = New Bullards Bar).

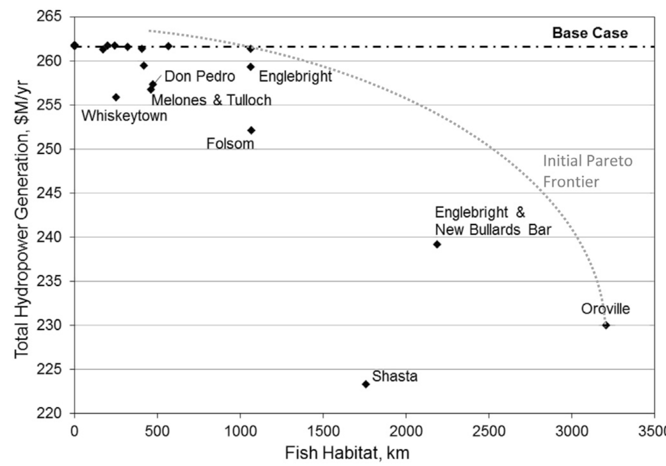

Fig. 10. Tradeoff between total hydropower generation and fish habitat with dams removed for climate change conditions (some dams not labeled so figure is readable).

Additional limitations of this study include the fish habitat analysis completed. We used estimates of suitable fish habitat, rather than the total river length to the next barrier upstream; however, habitat segments were not all connected in our analysis and so are an overestimate of habitat for anadromous fish or other migratory species. We assumed that passage exists for fish or other migratory biota downstream of removed dams (or would exist prior to removal). Suitable passage would need to be provided in many locations for this assumption to be true, such as at Nimbus Dam, La Grange Dam, Red Bluff Diversion Dam, and many others. This study also ignores lost habitat within reservoirs.

Finally, we estimate fish habitat, which is linked to fish population dynamics but is not a perfect substitute (Hayes et al., 1996). A fish population model would better estimate recruitment and provide additional information regarding bottlenecks in fish population dynamics and timing. Ecosystem health and function are also difficult to quantify, although multiple species population models or metrics of ecosystem health may better represent ecosystems from a more holistic standpoint (Fausch et al., 1984; Miller et al., 1988).

6. Conclusions

This study analyzes the economic benefit of dams as well as the potential to remove dams from a systems perspective (assuming all reservoirs are managed as a single system). This assumption is generally valid in regions with centralized water systems such as California, where most large dams are owned and operated by the State Water Project, the federal Central Valley Project, or a handful of local agencies. Many dam removal analyses take a narrower view to assess removals on a site-by-site basis, and do not assess environmental benefits or economic losses for their broader regions or from a systems analysis perspective.

The major findings of this study for removing dams in California are first, removing some dams relies on keeping and maintaining other dams to provide water supply and hydropower benefits. In line with this, our research indicates that Shasta and Oroville Dams are foundational to maintaining water supply benefits in California; water management in the state would fundamentally change without these dams. This finding is also useful to highlight where maintenance funding is best spent. Removing Whiskeytown, Pine Flat, Pardee and Camanche, or Englebright Dams may be promising to improve habitat for anadromous fish species and removing these dams warrants additional study.

Further, our study design – modeling dam removal with both historical conditions and future conditions with a warm, dry climate – sheds light on the changing benefit of dams through time. Drier climate conditions increase water scarcity more than removing any individual dam. With drier future conditions, storage space exists, but the entire system is short of water. This major finding contradicts the notion that additional surface storage is a promising adaptation for climate change and population growth. It also indicates that removing dams to increase habitat for anadromous species may be increasingly feasible in the future, and become a more promising solution to improve conditions for endangered and threatened species while maintaining economic benefits of water supply and hydropower with other reservoirs.

Finally, this paper explicitly considers fish habitat versus economic water demands for removing dams over a large geographic area using an existing water management model. All dams are not equal in terms of economic benefit or environmental harm. Matching the timing and volume of reservoir releases to water demands makes some dams more economically valuable than others, just as some block access to more upstream habitat (or cause other non-uniform environmental harm). Also, storage in watersheds has decreasing marginal economic benefit – the millionth acre foot of reservoir storage is less valuable than the first acre foot (Hazen, 1914). Reservoir storage capacity is a poor substitute for water deliveries or water scarcity in dam removal modeling and thus should not be used to represent the value of dams for removal analyses. However, storage capacity is the metric of economic benefit used by most dam removal studies (Poff and Hart, 2002; Hart et al., 2002). Better methods and models are needed for dam removal studies (Kemp and O'Hanley, 2010), and evaluating environmental data with existing hydro-economic models is a viable option to push dam removal analysis forward as a science.

Acknowledgments

We would also like to thank the following participants of a 2013 CALVIN short course, who helped to complete model runs and process results: Xueshan AI, Yihsu Chen, Tom Harmon, Basel Kitmitto, Joan Klipsch, Chan Modini, Timothy Nelson, Henry Pai, Karandev Singh, Kumaraswamy Sivakumaran, Nicholas Santos, Lucas Siegfried, Todd Steissberg, Josh Viers, Sandra Villamizar, Ashlee Vincent, and Dave Waetjen. We also thank Steven Lindley and the Southwest Fisheries Science Center of NMFS for sharing steelhead spatial data, Danielle Salt for data processing help, and Curtis Gray for sharing GIS expertise. This work was partially supported by the Public Policy Institute of California, with funding from the Pisces, Bechtel, and Packard Foundations. The collaboration of co-author Alvar Escriva-Bou was developed from a mobility stay funded by the Erasmus Mundus Programme of the European Commission under the Transatlantic Partnership for Excellence in Engineering – TEE Project. Finally, we thank anonymous reviewers for their helpful comments which improved this paper.

References

Bednarek, A.T., 2001. Undamming rivers: a review of the ecological impacts of dam removal. J. Environ. Manage. 27 (6), 803–814. http://dx.doi.org/10.1007/s002670010189.
Bernhardt, E.S., Palmer, M., 2005. Synthesizing US river restoration efforts. Science 308 (5722), 636–637.
Brown, P.H., Tullos, D., Tilt, B., Magee, D., Wolf, A.T., 2009. Modeling the costs and benefits of dam construction from a multidisciplinary perspective. J. Environ. Manag. 90, S303–S311.
Burnett, K.M., 2001. Relationships Among Juvenile Anadromous Salmonids, Their Freshwater Habitat, and Landscape Characteristics over Multiple Years and Spatial Scales in Elk River, Oregon. Oregon State University.
CALSIM webpage, 2002. http://modeling.water.ca.gov/hydro/model/ (accessed 11/2013).
Cayan, D.R., Maurer, E.P., Dettinger, M.D., 2008. Climate change scenarios for the California region. Clim. Change 87 (S1), 21–42. http://dx.doi.org/10.1007/s10584-007-9377-6.
CDWR, 2000. Dams Within Jurisdiction of the State of California. Bulletin 17–00. Sacrmento, CA.
Connell-Buck, C.R., Medellín-Azuara, J., Lund, J.R., Madani, K., 2011 November 24. Adapting California's water system to warm vs. dry climates. Clim. Change 109 (S1), 133–149. http://dx.doi.org/10.1007/s10584-011-0302-7.
Costanza, R., D'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'neill, R.V., Paruelo, J., 1997. The value of the world's ecosystem services and natural capital. Nature 387 (6630), 253–260.
Draper, A.J., Jenkins, M.W., Kirby, K.W., Lund, J.R., Howitt, R.E., 2003. Economic-engineering optimization for California water management. J. Water Resour. Plan. Manag. 129 (3), 155–164. http://dx.doi.org/10.1061/(ASCE)0733-9496(2003)129:3(155).
Eaton, J.G., Scheller, R.M., 1996. Effects of climate warming on fish thermal habitat in streams of the United States. Limnol. Oceanogr. 41, 1109–1115.
Engle, R.O., 2002. Distribution and Summer Survival of Juvenile Steelhead Trout (Oncorhynchus Mykiss) in Two Streams Within the King Range National Conservation Area, California. Humboldt State University.
Fausch, K.D., Karr, J.R., Yant, P.R., 1984 January 1. Regional application of an Index of biotic integrity based on stream fish communities. Trans. Am. Fish. Soc. 113 (1), 39–55. http://dx.doi.org/10.1577/1548-8659(1984)113<39:RAOAIO>2.0.CO;2. 2.
Ferreira, I.C., Tanaka, S.K., 2002. CALVIN Environmental Constraints.
Gibson, W., Daly, C., Kittel, T., Nychka, D., Johns, C., Rosenbloom, N., McNab, A., Taylor, G., 2002. Development of a 103-year High-resolution Climate Data Set for the Conterminous United States.
Gillenwater, D., Granata, T., Zika, U., 2006 December 1. GIS-based modeling of spawning habitat suitability for Walleye in the Sandusky river, Ohio, and implications for dam removal and river restoration. Ecol. Eng. 28 (3), 311–323. http://dx.doi.org/10.1016/j.ecoleng.2006.08.003.
Goulter, I., 1992 May 1. Systems analysis in water-distribution network design: from theory to practice. J. Water Resour. Plan. Manag. 118 (3), 238–248. http://dx.doi.org/10.1061/(ASCE)0733-9496(1992)118:3(238).
Gowan, C., Stephenson, K., Shabman, L., 2006. The role of ecosystem valuation in environmental decision making: hydropower relicensing and dam removal on the Elwha river. Ecol. Econ. 56 (4), 508–523. http://dx.doi.org/10.1016/j.ecolecon.2005.03.018.
Graf, W.L., 1999. Dam nation: a geographic census of American dams and their large-scale hydrologic impacts. Water Resour. Res. 35 (4), 1305. http://dx.doi.org/10.1029/1999WR900016.
Hanak, E., Lund, J., Dinar, A., Gray, B., Howitt, R., Mount, J., Moyle, P., Thompson, B., 2011. Managing California's Water: from Conflict to Reconciliation. Public Policy Institute of California, San Francisco, CA.
Hanemann, M., Dyckman, C., 2009 October. The San Francisco Bay-Delta: a failure of decision-making capacity. Environ. Sci. Policy 12 (6), 710–725. http://dx.doi.org/10.1016/j.envsci.2009.07.004.
Harou, J.J., Medellín-Azuara, J., Zhu, T., Tanaka, S.K., Lund, J.R., Stine, S., Olivares, M.A., Jenkins, M.W., 2010. Economic consequences of optimized water management for a prolonged, severe drought in California. Water Resour. Res. 46 (5). W05522.
Hart, D.D., Johnson, T.E., Bushaw-Newton, K.L., Horwitz, R.J., Bednarek, A.T., Charles, D.F., Kreeger, D.A., Velinsky, D.J., 2002 August 1. Dam removal:

challenges and opportunities for ecological research and river restoration. BioScience 52 (8), 669–682. http://dx.doi.org/10.1641/0006-3568(2002)052[0669:DRCAOF]2.0.CO;2. 2.
Harvey, B.C., White, J.L., Nakamoto, R.J., 2002 January 1. Habitat relationships and Larval Drift of native and nonindigenous fishes in neighboring tributaries of a coastal California river. Trans. Am. Fish. Soc. 131 (1), 159–170. http://dx.doi.org/10.1577/1548-8659(2002)131<0159:HRALDO>2.0.CO;2. 2.
Hayes, D.B., Ferreri, C.P., Taylor, W.W., 1996. Linking fish habitat to their population dynamics. Can. J. Fish. Aquatic Sci. 53 (S1), 383–390.
Hazen, A., 1914. Storage to be provided in impounding reservoirs for municipal water supply. Trans. Am. Assoc. Civ. Eng. 77, 1539–1669.
Howitt, R.E., Medellín-Azuara, J., MacEwan, D., Lund, J.R., 2012 December. Calibrating disaggregate economic models of agricultural production and water management. Environ. Model. Softw. 38 (0), 244–258. http://dx.doi.org/10.1016/j.envsoft.2012.06.013.
James, L.A., 2005 October 1. Sediment from hydraulic mining detained by englebright and small dams in the Yuba Basin. Geomorphology 71 (1–2), 202–226. http://dx.doi.org/10.1016/j.geomorph.2004.02.016.
Jenkins, M.W., 2001. Appendix 2H: calibration process details (2001). In: Jenkins, et al. (Eds.), Improving California Water Management: Optimizing Value and Flexibility. Final Report. Available at: http://calvin.ucdavis.edu (Accessed 2013).
Jenkins, M.W., 2004. California Urban Water Demands for Year 2050. CEC-500-2005-195. Davis, CA.
Johnson, S.E., Graber, B.E., 2002. Enlisting the social sciences in decisions about dam removal. BioScience 52 (8), 731–738.
Kareiva, P.M., 2012. Dam choices: analyses for multiple needs. Proc. Natl. Acad. Sci. 109 (15), 5553–5554.
Kemp, P.S., O'Hanley, J.R., 2010. Procedures for evaluating and prioritising the removal of fish passage barriers: a synthesis. Fish. Manag. Ecol. 17 (4), 297–322.
Knapp, R.A., 1996. Non-native Trout in Natural Lakes of the Sierra Nevada: an Analysis of Their Distribution and Impacts on Native Aquatic Biota.
Kuby, M.J., Fagan, W.F., ReVelle, C.S., Graf, W.L., 2005 August. A multiobjective optimization model for dam removal: an example trading off Salmon passage with hydropower and water storage in the Willamette Basin. Adv. Water Resour. 28 (8), 845–855. http://dx.doi.org/10.1016/j.advwatres.2004.12.015.
Landis, J.D., Reilly, M., 2003. How We Will Grow: Baseline Projections of California's Urban Footprint through the Year 2100. Integrated Land Use and Environmental Models, pp. 55–98.
Lindley, S.T., Schick, R.S., Agrawal, A., Goslin, M., Pearson, T.E., Mora, E., Anderson, J.J., et al., 2006. Historical population structure of Central Valley steelhead and its alteration by dams. San. Francisco Estuary Watershed Sci. 4 (1).
Lund, J.R., Hanak, E., Fleenor, W., Bennett, W., Howitt, R., Mount, J., Moyle, P., 2010. Comparing Futures for the Sacramento-San Joaquin Delta. University of California Press, Berkeley, CA.
Maurer, E.P., Hidalgo, H.G., 2008. Utility of daily vs. monthly large-scale climate data: an intercomparison of two statistical downscaling methods. Hydrol. Earth Syst. Sci. 12 (2), 551–563.
Medellín-Azuara, J., Harou, J.J., Olivares, M., Madani-Larijani, K., Lund, J.R., Howitt, R.E., Tanaka, S.K., Jenkins, M.W., Zhu, T., 2008. Adaptability and adaptations of California's water Supply system to dry climate warming. Clim. Change 87 (0), 75–90. http://dx.doi.org/10.1007/s10584-007-9355-z.
Medellín-Azuara, J., Howitt, R.E., MacEwan, D.J., Lund, J.R., 2011. Economic impacts of climate-related changes to California agriculture. Clim. Change 109 (1), 387–405. http://dx.doi.org/10.1007/s10584-011-0314-3.
Medellín-Azuara, J., Lund, J., Howitt, R., 2007 September 1. Water supply analysis for restoring the Colorado river Delta, Mexico. J. Water Resour. Plan. Manag. 133 (5), 462–471. http://dx.doi.org/10.1061/(ASCE)0733-9496(2007)133:5(462).
Michaud, D., Apostolakis, G., 2006 December 1. Methodology for ranking the elements of water-supply networks. J. Infrastruct. Syst. 12 (4), 230–242. http://dx.doi.org/10.1061/(ASCE)1076-0342(2006)12:4(230).
Miller, D.L., Hughes, R.M., Karr, J.R., Leonard, P.M., Moyle, P.B., Schrader, L.H., Thompson, B.A., Daniels, R.A., Fausch, K.D., Fitzhugh, G.A., 1988. Regional applications of an index of biotic integrity for use in water resource management. Fisheries 13 (5), 12–20.
Moyle, P.B., Randall, P.J., 1998. Evaluating the biotic integrity of watersheds in the sierra Nevada, California. Conserv. Biol. 12 (6), 1318–1326. http://dx.doi.org/10.1111/j.1523-1739.1998.97161.x.
Moyle, P.B., Israel, J.A., Purdy, S.E., 2008. Salmon, Steelhead, and Trout in California: Status of an Emblematic Fauna.
Myrick, C.A., Cech, J.J., 2001. Temperature Effects on Chinook Salmon and Steelhead: a Review Focusing on California's Central Valley Populations. Bay-Delta Modeling Forum.
Nationalatlas gov, 2013. National Atlas of the United States of America. California Precipitation. Accessed July 15. http://maps.redcross.org/website/Maps/Images/California/pageprecip_ca3.pdf.
Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005 April 15. Fragmentation and flow regulation of the World's large river systems. Science 308 (5720), 405–408. http://dx.doi.org/10.1126/science.1107887.
Null, S.E., Bartolomeo, E., Lund, J.R., Hanak, E., 2012. Managing California's Water: insights from interviews with water policy experts. San. Francisco Estuary Watershed Sci. 10 (4).
Null, S.E., Lund, J.R., 2006 April 1. Reassembling hetch hetchy: water supply without O'Shaughnessy dam. J. Am. Water Resour. Assoc. 42 (2), 395–408. http://dx.doi.org/10.1111/j.1752-1688.2006.tb03846.x.
O'Hanley, J.R., 2011. Open rivers: barrier removal planning and the restoration of free-flowing rivers. J. Environ. Manag. 92 (12), 3112–3120. http://dx.doi.org/10.1016/j.jenvman.2011.07.027.
Pejchar, L., Warner, K., 2001. A river might run through it again: criteria for consideration of dam removal and interim lessons from California. Environ. Manag. 28 (5), 561–575. http://dx.doi.org/10.1007/s002670010244.
Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Brian, D., Sparks, R.E., Stromberg, J.C., Richter, B.D., 1997. A Paradigm for River Conservation and Restoration, vol. 47 (11), pp. 769–784.
Poff, N.L., Hart, D.D., 2002. How dams vary and why it matters for the emerging science of dam removal. BioScience 52 (8), 659–668. http://dx.doi.org/10.1641/0006-3568(2002)052[0659:HDVAWI]2.0.CO;2.
Pohl, M.M., 2002. Bringing down our dams: trends in American dam removal rationales. J. Am. Water Resour. Assoc. 38 (6), 1511–1519. http://dx.doi.org/10.1111/j.1752-1688.2002.tb04361.x.
Power, M.E., Dietrich, W.E., Finlay, J.C., 1996. Dams and downstream aquatic biodiversity: potential food web consequences of hydrologic and geomorphic change. Environ. Manag. 20 (6), 887–895. http://dx.doi.org/10.1007/BF01205969.
Reisner, M., 1993. Cadillac Desert: the American West and its Disappearing Water. Penguin Books, New York, NY.
Ritzema, R.S., 2002. Hydropower in the CAVLIN Model. In: Appendix D to CALVIN Report: Talking about the Weather: Climate Warming and California's Water Future. UC Davis.
Roberts, S.J., Gottgens, J.F., Spongberg, A.L., Evans, J.E., Levine, N.S., 2007. Assessing potential removal of low-head dams in urban settings: an example from the Ottawa river, NW Ohio. J. Environ. Manag. 39 (1), 113–124. http://dx.doi.org/10.1007/s00267-005-0091-8.
Stevens, D.E., Miller, L.W., 1983 October 1. Effects of river flow on abundance of Young Chinook Salmon, American Shad, Longfin Smelt, and Delta Smelt in the Sacramento-San Joaquin river system. North Am. J. Fish. Manag. 3 (4), 425–437. http://dx.doi.org/10.1577/1548-8659(1983)3<425:EORFOA>2.0.CO;2.
Tanaka, S.K., Connell-Buck, C.R., Madani, K., Medellin-Azuara, J., Lund, J.R., Hanak, E., 2011. Economic costs and adaptations for alternative regulations of California's Sacramento-San Joaquin Delta. San. Francisco Estuary Watershed Sci. 9 (2).
Tanaka, S.K., Zhu, Tingju, Lund, J.R., Howitt, R.E., 2006. Climate warming and water management adaptation for California. Clim. Change 76, 361–387.
Tomsic, C.A., Granata, T.C., Murphy, R.P., Livchak, C.J., 2007 July 2. Using a coupled eco-hydrodynamic model to predict habitat for target species following dam removal. Ecol. Eng. 30 (3), 215–230. http://dx.doi.org/10.1016/j.ecoleng.2006.11.006.
USACE, 1998. National Inventory of Dams. Accessed: July 2013.
USACE, 1999. HEC-PRM Package. Hydrologic Engineering Center, Davis, CA.
US Bureau of Reclamation, 1997. Central Valley Project Improvement Act Programmatic Environmental Impact Statement (CD-ROM). USBR, Sacramento, CA.
Waples, R.S., 1999. Dispelling some myths about hatcheries. Fisheries 24 (2), 12–21. http://dx.doi.org/10.1577/1548-8446(1999)024<0012:DSMAH>2.0.CO;2.
Williams, J.E., Nehlsen, W., Lichatowich, J.A., 1991. Pacific Salmon at the crossroads: stocks at risk from California, Oregon, Idaho, and Washington. Fisheries 16 (2), 4–21. http://dx.doi.org/10.1577/1548-8446(1991)016<0004:PSATCS>2.0.CO;2.
Winter, B.D., Crain, P., 2008 December 1. Making the case for ecosystem restoration by dam removal in the Elwha river, Washington. Northwest Sci. 82 (sp1), 13–28. http://dx.doi.org/10.3955/0029-344X-82.S.I.13.
Wurbs, R.A., 1996. Modeling and Analysis of Reservoir System Operations. Prentice-Hall.
Yeh, W.W.G., 1985. Reservoir management and operations models: a state-of-the-art review. Water Resour. Res. 21 (12), 1797–1818.
Yoshiyama, R.M., Fisher, F.W., Moyle, P.B., 1998 August 1. Historical abundance and decline of Chinook Salmon in the Central Valley region of Californa. North Am. J. Fish. Manag. 18 (3), 487–521. http://dx.doi.org/10.1577/1548-8675(1998)018<0487:HAADOC>2.0.CO;2. 2.
Zheng, P.Q., Hobbs, B.F., Koonce, J.F., 2009. Optimizing multiple dam removals under multiple objectives: linking tributary habitat and the Lake Erie ecosystem. Water Resour. Res. 45 (12), W12417. http://dx.doi.org/10.1029/2008WR007589.
Zhu, Tingju, Jenkins, M.W., Lund, J.R., 2005. Estimated impacts of climate warming on California water availability under twelve future climate scenarios. J. Am. Water Resour. Assoc. 41 (5), 1027–1038. http://dx.doi.org/10.1111/j.1752-1688.2005.tb03783.x.